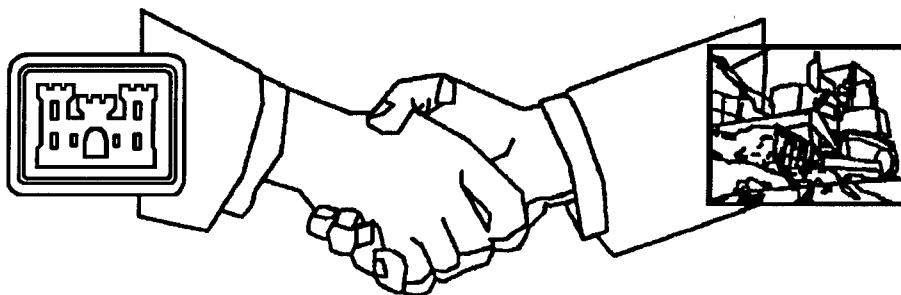
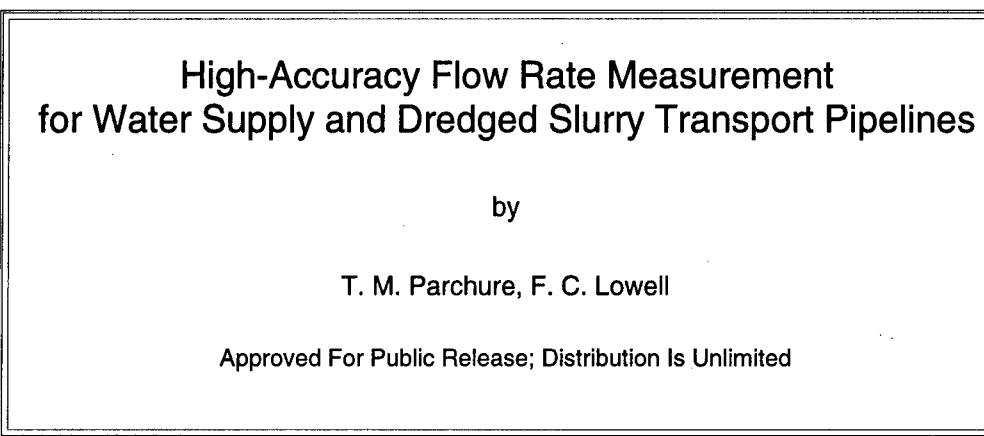




**US Army Corps
of Engineers**
Waterways Experiment
Station

Final Report
CPAR-CHL-97-1
August 1997

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM



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**A Corps/Industry Partnership to Advance
Construction Productivity and Reduce Costs**

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High-Accuracy Flow Rate Measurement for Water Supply and Dredged Slurry Transport Pipelines

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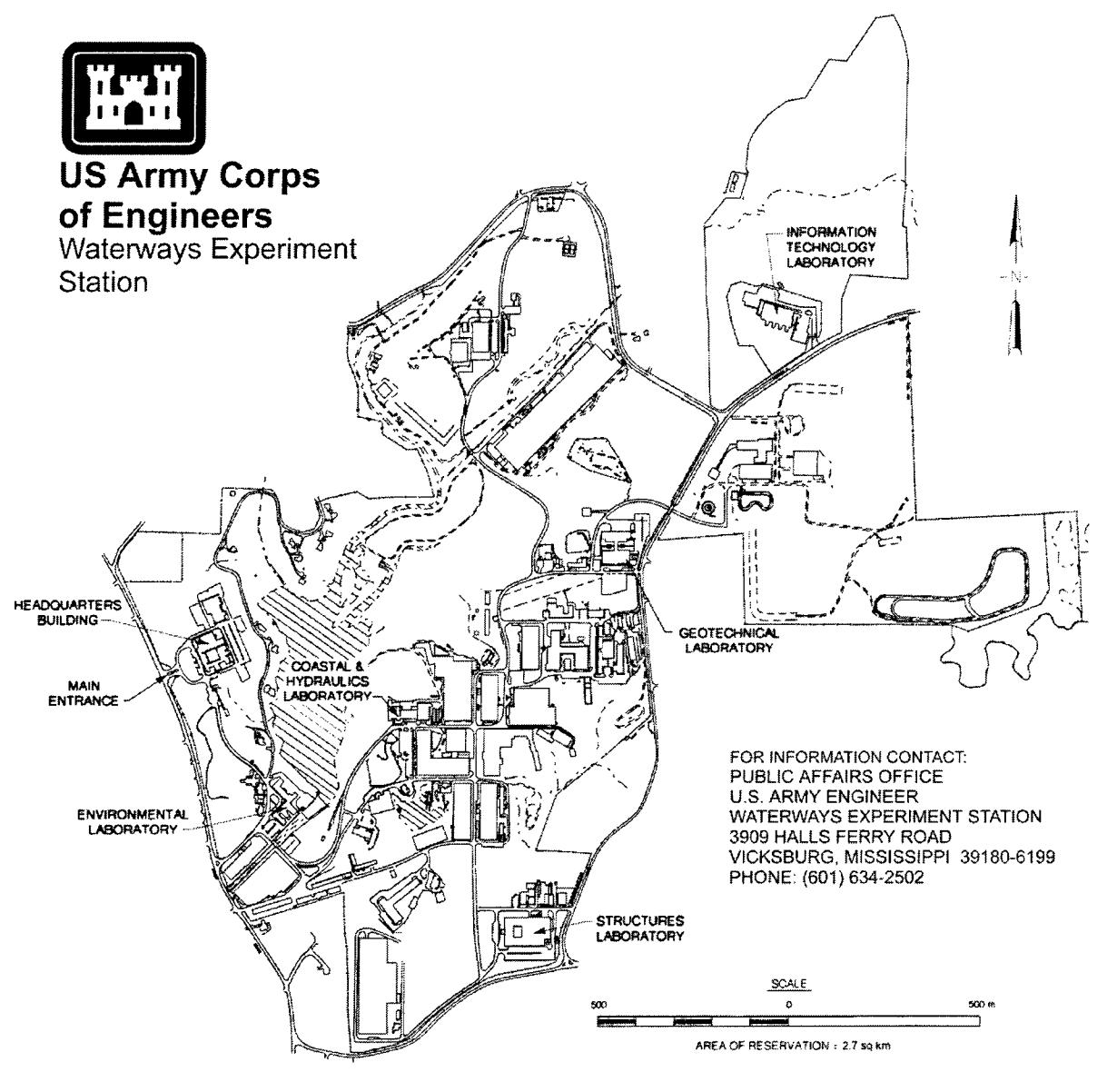
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Contents

Preface	vii
1—Project Background	1
Background	1
Acoustic Flow Meter Development	3
Theory of Operation	7
Project Objective	9
The Product	9
2—Materials and Test Facilities	10
Material Selection	10
Array Design	10
Laboratory Facilities at ORE	11
Other Test Facilities	16
3—Research and Development Introduction	18
Need For a New Flow Meter	18
New Acoustic Flow Meter	19
System Accuracy of Acoustic Flow Meter	21
Path Errors	23
Integration Errors	24
Summary of Error Sensitivity	29
Research Needs For New Flow Meter	29
Developmental Problems	33
Development Stages and Achievements	33
Work Done By Subcontractor	34
4—Research and Development	36
Stage 1	36
Stage 2	37
Stage 3	38
Stage 4	40
Alden Laboratory Test	41

Stage 5	44
Stage 6	45
Stage 7	45
Colton Field Test	46
Stage 8	50
Stage 9	52
Stage 10	52
Stage 11	53
Stage 12	54
Stage 13	55
<i>Wheeler Field Test</i>	56
Stage 14	59
Stage 15	59
Software for Data Processing	59
 5—Conclusions and Recommendations	62
General Conclusions	62
Potential Impact on U.S. Industry	66
Potential Impact on the Corps of Engineers	66
Recommendations	67
Further Information	67
 6—Marketing and Technology Transfer	68
Marketing Plans and Related Activities	68
Cost	70
Technology Transfer	71
 References	72
Appendix A: Mathematical Relationships for Travel of Acoustic Signal and Technical Details of New Flow Meter	A1
Appendix B: United States Patent Number 5,228,347 Dated July 20, 1993, Awarded to F. C. Lowell and R. H. Lyon Method and Apparatus for Measuring Flow by Using Phase Advance	B1
Appendix C: Report Dated 15 August 1991 From R. H. Lyon Corporation, Experimental Results On the Design of an Externally Mountable Acoustic Flow Meter	C1
Appendix D: Report Dated 27 May 1994 From R. H. Lyon Corporation, Further Results of Sensitivity Analysis of Transducer Performance	D1
Appendix E: Frequency Response of Tank and Simulation Obtained by ORE	E1

List of Figures

Figure 1.	Turbine efficiency measurement using different methods . . .	4
Figure 2.	Discharge measurement using different methods	5
Figure 3.	Average difference from reference discharge using different methods	6
Figure 4.	Flow velocity calculation for an acoustic travel time meter path	8
Figure 5.	Layout of PVDF transducer array	12
Figure 6.	Typical PVDF array cross section	13
Figure 7.	Block diagram of prototype flow meter	14
Figure 8.	Testing and calibration tank	15
Figure 9.	Closeup of testing and calibration tank	15
Figure 10.	Steel tank for testing clamp-on type transducers	16
Figure 11.	Output of test result at ORE facility	17
Figure 12.	Schematic representation of two- and three-path flow meter	20
Figure 13.	Close-up of new transducer	21
Figure 14.	Hardware and software development unit	22
Figure 15.	Data processing hardware	22
Figure 16.	Weights of sections for accurate flow measurement	25
Figure 17.	Meter factor versus Reynolds number curves (linear plot)	27
Figure 18.	Meter factor versus Reynolds number (log plot)	28
Figure 19.	Initial proposal of flow meter configuration (ORE Drg. 7400-BE-0733)	31
Figure 20.	Flow meter calibration at Alden Research Laboratory, 609-mm- (24-in.-) diameter pipe	42

Figure 21.	Test results of handmade arrays, 914-mm (36-in.) flow meter calibration	43
Figure 22.	Installation of transducer on penstock at Colton	48
Figure 23.	Closeup of transducer installed on penstock	48
Figure 24.	Comparison of results obtained by intrusive and externally mounted flow meters, two-path flow meter versus 7500, 4.1-m (13.5-ft) diameter at Colton, NY	49
Figure 25.	Transducer being installed on dredge pipe of <i>Wheeler</i>	57
Figure 26.	Data acquisition system used on <i>Wheeler</i>	58
Figure 27.	An example of test record obtained on dredge pipe	58
Figure 28.	Flowchart of Accusonic flow meter operation	61

Preface

The joint Construction Productivity Advancement Research (CPAR) project, "High-Accuracy Flow Rate Measurement for Water Supply and Dredged Slurry Pipelines," between ORE and the U.S. Army Corps of Engineers on the development of a new acoustic flow meter described in this report started in March 1993. The project continued over 3-1/2 years and was completed in September 1996. ORE International invested an amount of \$500,000 for this project. In addition, the U.S. Army Corps of Engineers invested \$500,000, making this a million-dollar project.

Successful completion of this large project was possible only because of the excellent cooperation and assistance offered by a large number of individuals and organizations. In particular, a deep sense of gratitude is expressed to the following:

- a. R. H. Lyon, Inc., provided technical support, conducted fundamental research on the performance of the PVDF transducers, and provided results of computer output on several problems encountered from time to time during development stages.
- b. Alden Research Laboratory provided research facilities and weighing tank facilities for testing of the flow meter in their laboratory.
- c. Authorities of the Niagara Mohawk Power Company gave permission for testing of the flow meter on the penstock at their hydroelectric power station at Colton, NY.
- d. The New Orleans District of the U.S. Army Corps of Engineers gave permission to install transducers on a dredge pipeline, provided accommodation and food on the dredge *Wheeler*, and cooperated during field tests.

The research work was conducted by personnel of ORE International, Inc., and the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS.

Dr. Trimbak M. Parchure, Research Hydraulic Engineer, Sedimentation Engineering and Dredging Group, Estuarine Branch, Waterways and Estuaries Division, was the Principal Investigator for the project. Francis C.

Lowell, President, Accusonic Division, ORE International, was the Principal Investigator of the partner. Dr. Parchure prepared this report jointly with Mr. Lowell. The project work was conducted under general supervision of Messrs. Allen Teeter, Leader, Sedimentation Engineering and Dredging Group, William H. McAnally, Jr., Chief, Waterways and Estuaries Division; and Richard A. Sager, Assistant Director, and Dr. James R. Houston, Director, CHL. Mr. William F. McCleese of WES monitored the progress of this project, provided advice, and maintained constant liaison with personnel, Headquarters, U.S. Army Corps of Engineers (HQUSACE), Washington, DC. The technical monitors at HQUSACE were Messrs. Sam Powell, Tom Verna, and Frederick Eubank.

This report is being published by the WES Coastal and Hydraulics Laboratory (CHL). The CHL was formed in October 1996 with the merger of the WES Coastal Engineering Research Center and Hydraulics Laboratory. Dr. James R. Houston is the Director of the CHL, and Messrs. Richard A. Sager and Charles C. Calhoun, Jr., are Assistant Directors.

During the preparation and publication of this report, Dr. Robert W. Whalin was Director of WES and COL Bruce K. Howard, EN, was Commander.

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1 Project Background

Background

Measurement of volume flow rate and velocity of water in pipes and open channels is essential for evaluating and monitoring the performance of hydroelectric power stations and water resources structures and revenue metering, to name a few applications. Typical examples include penstocks of hydroelectric projects, cooling water pipes of thermal power stations, irrigation systems, canals, rivers, closed conduits, and water supply and wastewater pipes.

At the present time there are several international code-accepted methods for flow measurement, including the acoustic method, which are covered in detail in their respective test codes, viz. American Society of Mechanical Engineers (ASME) Performance Test Code 18-1992 (ASME 1993) and American National Standards Institute (ANSI) Standard MFC-5M-1985 (ANSI/ASME 1985).

The following are some of the typical methods used in the past for flow measurements:

- a. *Pressure-time method.* Flow measurement is initiated by closing the wicket gates in one continuous movement with the unit connected to the electrical grid, and recording the resultant pressure wave against time. Data are recorded immediately preceding, during, and for a short time after the gate closure. The flow rate is computed using the net area of the pressure time diagram, the constant of the apparatus, conduit size, and the wicket gate leakage.
- b. *Current meter method.* Depending on the accuracy requirement and pipe size, 10 to 100 current meters are installed in a grid pattern supported by a frame in the pipe. For example, Hydro-Quebec, Canada, used 52 field current meters inside a penstock for determining flow rate.
- c. *Dye dilution method.* This method consists of injecting a known concentration of dye into flowing water and sampling the water at a point downstream after mixing has occurred. Calibrated volumetric

dye injection pumps are used in this method. The sample is then compared using a fluorometer against a standard solution of known concentration to determine its dye concentration. The flow rate is calculated from the initial dye concentration, injection rate, and the concentration of the dye in the sample.

- d. Salt velocity method.* This method consists of injecting a concentrated salt solution from a distribution manifold for a short interval of time, usually about 1 second, into flowing water inside a penstock. The salt solution disperses throughout the cross section of the penstock as it moves downstream of the injection point. Increase in the electrical conductivity of water is measured by electrodes at two locations. The rate of flow is computed from the volume of the penstock between the two adjacent electrodes and the time it takes for the salt cloud to travel from one electrode to the next.
- e. Acoustic flow meters.* There are several types of acoustic flow meters. This report describes development of a multipath differential travel time type meter, generally acknowledged to be the most accurate. This is currently covered by both ASME (ANSI/ASME 1985) and International Power Test Codes (International Electrotechnical Commission 1991). Acoustic flow meters are also used in noncircular pipes and open channels. Open channel applications are covered by a separate American Society for Testing and Materials (ASTM) code (ASTM 1984).

Typically, an acoustic flow meter contains up to four paths in one or two planes, depending on the accuracy requirements. The path location depends on the flow rate integration method used. Usually the planes are at an angle of 0.79 or 1.13 rad (45 or 65 deg) to the flow direction. The average flow velocity for each path is determined by measurement of the difference in acoustic travel time of a high-frequency (100- to 1,000-kHz) signal propagated upstream and downstream between the two transducers forming each path. Flow rate is then determined by integrating the velocities obtained from all paths in each plane and averaging the flows when two planes are used.

Evaluations of different methods used for flow measurements have been performed by several different organizations over the past few years. One of the most comprehensive reports is entitled "Acoustic Flow Measurement Evaluation Project" (Lang, Thomas, and Beauchamp 1987) sponsored by the Electric Power Research Institute (EPRI).

As a part of this study, the U.S. Bureau of Reclamation (USBR) compared flow measurements at the Grand Coulee Pumping-Generating plant unit P/G 9 using the following flow meters/methods:

- a. Acoustic flow meter manufactured by the Accusonic Division, Ferranti ORE, Inc.*

- b.* Acoustic flow meter made by Westinghouse Corporation.
- c.* Dye dilution method.
- d.* Pressure-time method.
- e.* Salt velocity method.
- f.* Volumetric method.

USBR prepared a report for the EPRI giving a comparison of measurements made with different methods and devices (Heigel, Lewey, and Greenwood 1986). Selected results from that report are shown in Figures 1, 2, and 3. These give the turbine efficiency, turbine discharge, and average difference from measured discharge, respectively, using each of these methods.

Acoustic Flow Meter Development

Although used successfully and extensively over the past few decades, a multipath acoustic flow meter had the disadvantage of having its acoustic transducers mounted either inside the pipe or through holes in the pipe wall, so that the face of the transducer was perpendicular to the acoustic path axis. This required dewatering the pipe and access to the inside of the pipe.

Although so-called clamp-on travel time flow meters are used extensively in smaller pipelines, their use has been limited to applications that do not require high accuracy, because the only possible path location has been limited to diametrical paths. This path location, even if used on multiple (crossed) diameters, is inherently prone to significant integration errors where onsite calibration is not possible. Even when calibration is possible, the meter may exhibit significant nonlinearities under changing flow conditions, particularly when upstream elbows, valves, and bifurcations are present. Furthermore, their design inherently requires the use of high frequencies, limiting their usefulness in large pipelines or pipes with sediment loads.

It may be noted that clamp-on Doppler flowmeters are also routinely used for water flow measurement. These devices are inexpensive and reliable. However, even under good conditions, they lack even the limited accuracy of a single-path diametrical meter. Their accuracy is further reduced when measuring flows with variable concentrations of acoustic scatterers, such as air bubbles or sediment.

The advantages of the “clamp-on” type flow meter are that it requires no contact with the fluid, no welding or cutting of pipe, and no operational

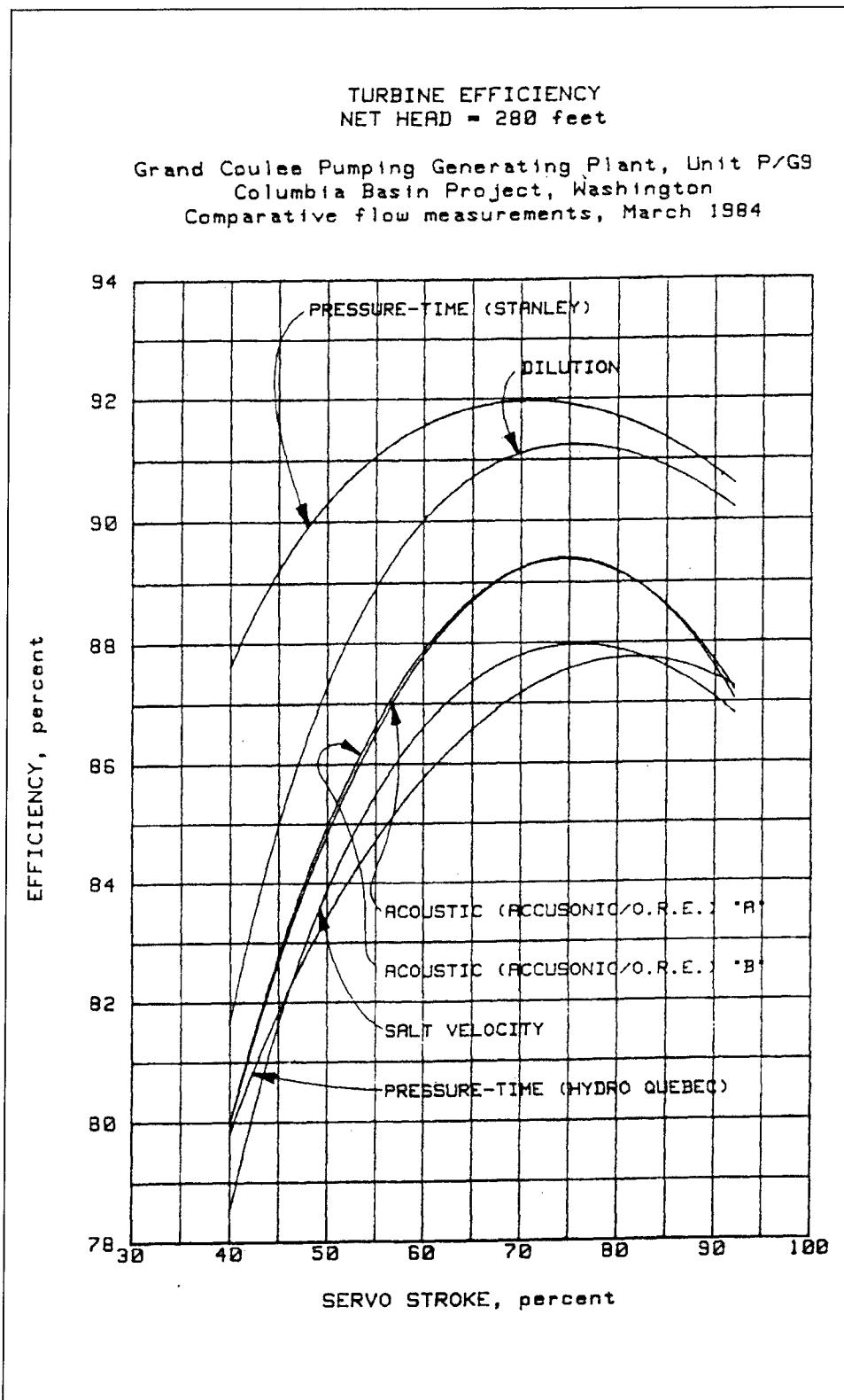


Figure 1. Turbine efficiency measurement using different methods (from Heigel, Lewey, and Greenwood 1986). To convert head in feet to meters, multiply by 0.3048

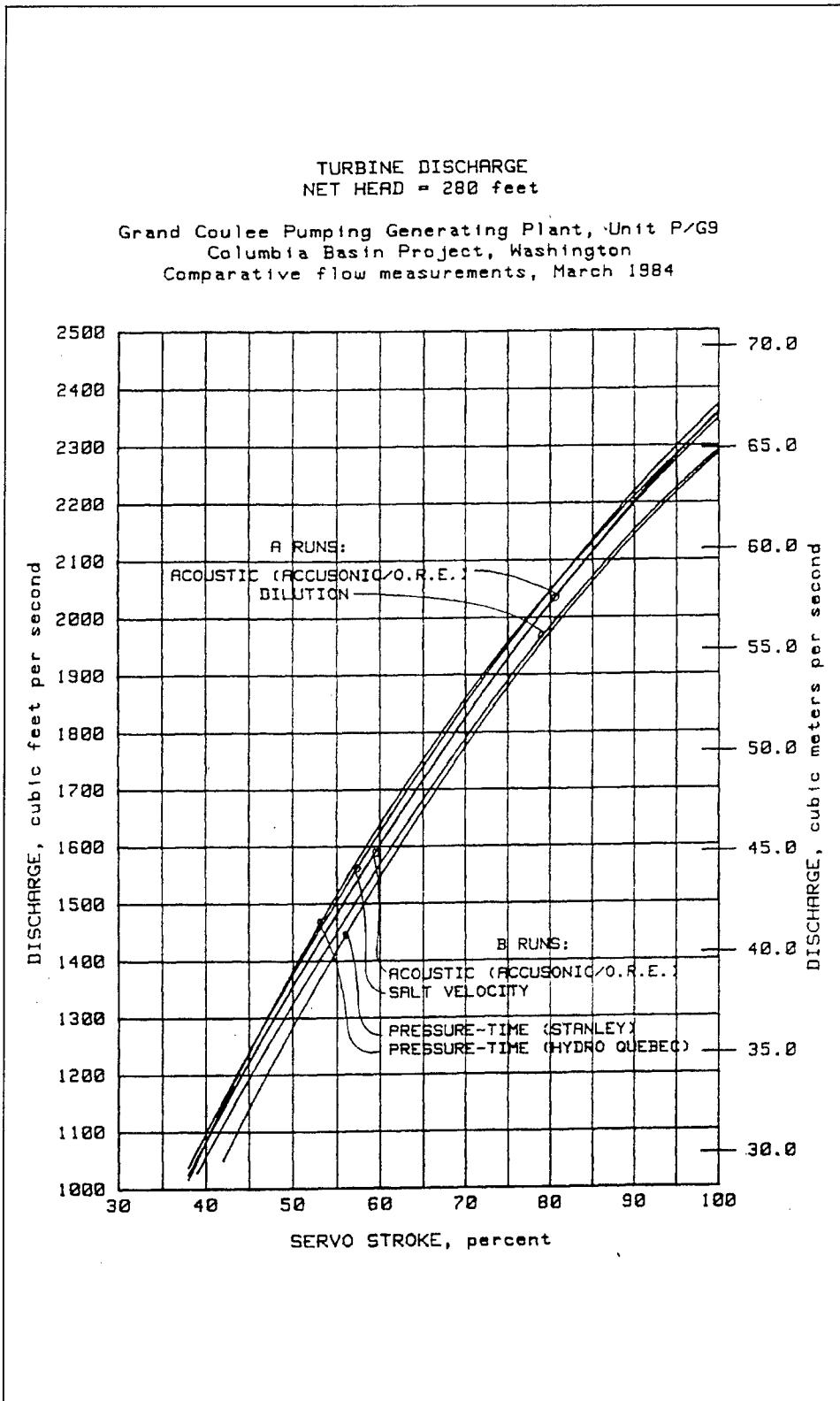


Figure 2. Discharge measurement using different methods (from Heigel, Lewey, and Greenwood 1986). To convert net head in meters, multiply by 0.3048

TURBINE DISCHARGE
 PERCENT DIFFERENCE FROM REFERENCE
 AVERAGE OF POINTS

Grand Coulee Pumping Generating Plant, Unit P/G9
 Columbia Basin Project, Washington
 Comparative flow measurements, March 1984

NOTE: reference = average of salt velocity points.

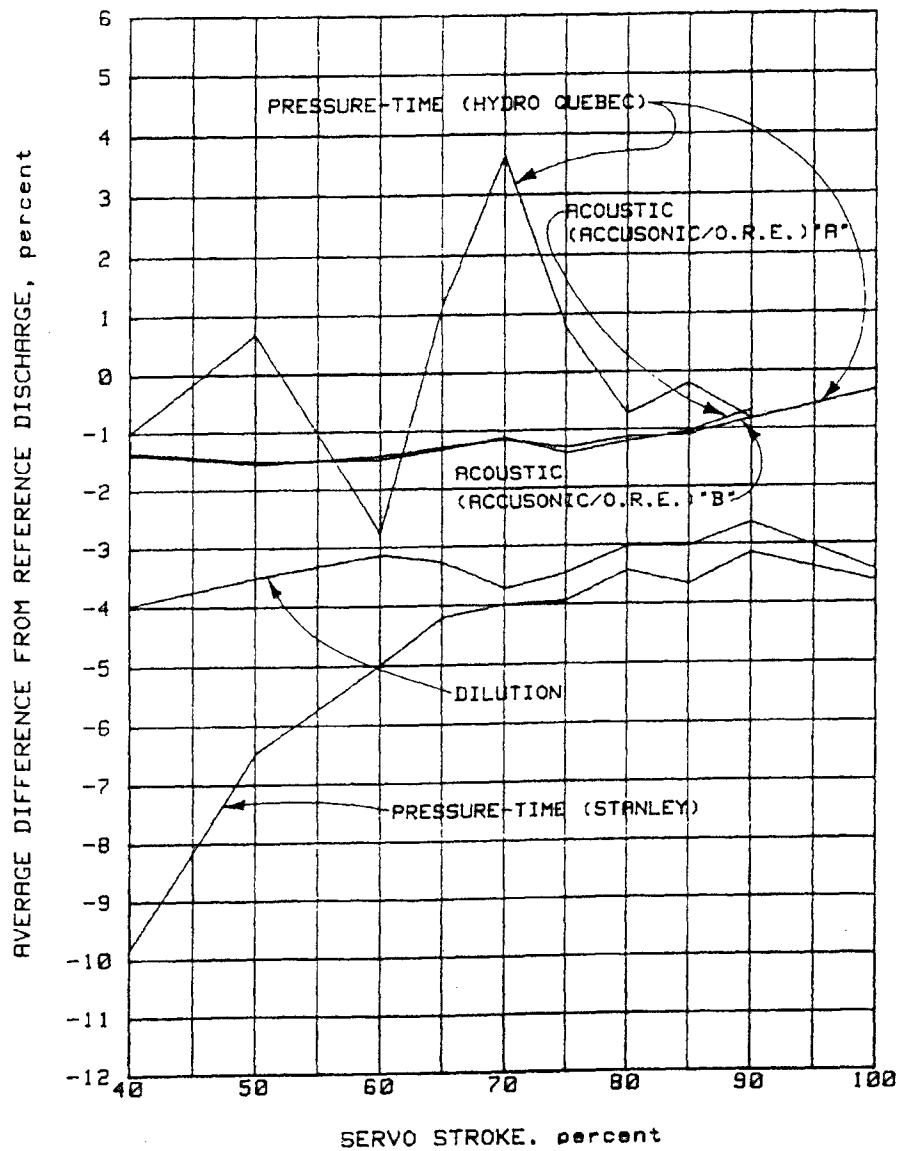


Figure 3. Average difference from reference discharge using different methods (from Heigel, Lewey, and Greenwood 1986)

shutdown for installation or maintenance. In addition the installation is quick, easy, and low cost.

Hence, despite the limitations of existing technology, ORE International has continued to seek a means by which the inherent advantages of the clamp-on approach could be combined with the high accuracy achievable to date only with intrusive, multiple-path acoustic flow meters, or expensive magnetic flow meters. A means of achieving such a combination of features has now been identified through the company-funded Research and Development program. The Construction Productivity Advancement Research (CPAR) Proposal sought the participation of the U.S. Army Corps of Engineers in speeding the transition from a laboratory-proven concept to a market-ready device.

Prior to this development project, chordal multipath high-accuracy flow meters with externally mounted transducers were impossible to build. In 1992, the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, initiated a collaborative research effort with the Accusonic Division of ORE International, Inc., for developing a multiple chordal path, externally mountable, transducer flow meter for large penstocks and sediment-laden dredge slurry pipes. This report describes this project.

Theory of Operation

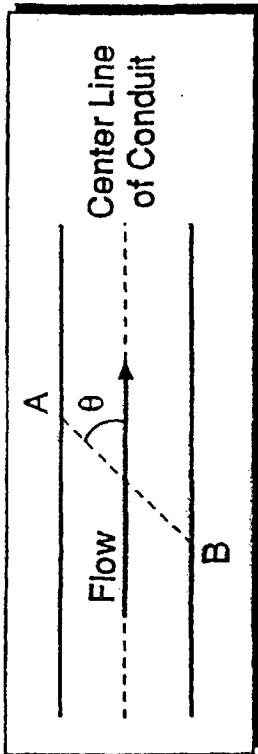
Acoustic flow meters fall under one of two categories. The first type is the Doppler flow meter, which operates by measuring the Doppler shift in frequency produced by fluid motion between transmitted and received signals. In this device, both the transducers are located on the same side of the pipe. It requires the presence of ultrasonic reflective bodies such as suspended solids or gas bubbles in water. With clear water, elaborate and specialized circuitry is needed for filtering, processing, and running spectral analysis of the signal.

The second type, manufactured by Accusonic, is a differential travel time meter. This system measures the difference in travel time between signals propagating upstream and downstream between multiple pairs of transducers. The measurement principle is explained in Figure 4. It may be seen from this figure that under no flow conditions will the travel time in each direction be the same. Under fluid flow conditions, the travel time in the downstream direction will be less than that in the upstream direction.

The velocity formula given in Figure 4 uses the total travel time to correct the velocity readings for variations in the speed of sound in the fluid. Also it is important to note that if the path lengths and angles are accurately known, it is not necessary to "wet-calibrate" the meter; it is sufficient to enter the "as-built" path dimensions along with the pipe diameter to have a "dry-calibrated" volumetric flow meter. This is an extremely

Flow Velocity Calculation

$$\bar{V} = \frac{(T_{up} - T_{down}) * L}{T_{up} * T_{down} \cdot 2 \cos \theta}$$



where:

T_{up} = Travel time of the acoustic pulse in the upstream direction
 T_{down} = Travel time of the acoustic pulse in the downstream direction
 L = Acoustic path length (distance between the transducer faces)
 \bar{V} = Average velocity of the water at the level of the acoustic path
 θ = Angle between the acoustic path and the direction of flow

Figure 4. Flow velocity calculation for an acoustic travel time meter path

important feature of this meter type as it is very difficult to calibrate flow meters in larger pipe sizes, as can be seen by the summary of other flow measurement methods presented in the section, “Background”.

Project Objective

The project objective was to develop the first acoustic flow meter that combines the high absolute accuracy of multipath measurement with the economy and simplified installation of less accurate “clamp-on” flow meters for application in water supply and slurry transport industries.

The Product

It was proposed that the product developed as a result of this research be a two-path acoustic flow meter transceiver, consisting of conformal phased array transducers along with associated signal generation and processing hardware and software. The transducers as presently conceived will be constructed of a relatively new transducer material, polyvinylidene fluoride (PVDF). This material was found to be ideal for a flexible production transducer easily installable in the field conforming to a variety of pipe exterior dimensions. The transceiver and transducers were proposed to be interfaced into an existing Accusonic flow meter design.

2 Materials and Test Facilities

Material Selection

After several alternatives were considered, strips of PVDF were selected as transducers. ORE is probably the first company to try PVDF for acoustic flow meters. The relevant property of this material for the particular application is that it transforms an electrical signal into a mechanical motion and conversely a mechanical force into an electrical response. It is therefore possible to use it for inducing vibrations in the pipe wall at one location, as well as for detecting the transmitted vibrations at the other side of the pipe. The frequency range is very broad, ranging from 0.001 Hz to GHz, and the acoustic impedance is low. Lead backing was used to provide a reaction mass.

The PVDF strips 152 by 13 mm (6 by 0.5 in.) in size and 28/52 microns in thickness were tested to determine their suitability in forming arrays of various shapes and transmitting signals of the required specifications. It was found in June 1993 that most of the units supplied by the manufacturer were defective. Replacement units were procured from the manufacturer.

Further trials indicated that 28-micron-thick strips were too thin and were not suitable for signal transmission. Strips 51 and 104 microns thick appeared satisfactory.

Installation of individual strips is very tedious and time consuming. ORE devised an array about 152 by 152 mm (6 by 6 in.) in size on which the individual strips could be electrically insulated from one another. Lead backing was formed as a single piece. This greatly facilitated installation and also reduced construction tolerances.

Array Design

One of the main efforts of ORE was testing of different shapes of arrays in an attempt to create a shaded array for minimum sidelong excitation of the pipe wall. This was not completely satisfactory. This part of

the research work was essential because it would minimize the noise signal transmitted through the pipe wall. ORE constructed this configuration and conducted trials using their laboratory facilities. It was found that although the configuration was better than the previous layout in meeting its objective, the overall efficiency of transmission was rather low.

An array with a shielded configuration recommended by R. H. Lyon was built¹. This was mounted underneath machined lead strips on the experimental 1.2-m- (4-ft-) diameter steel pipe facility at ORE. Initial testing was done for a chordal alignment of 0.5 rad (30 deg). The array was made larger than the previous configuration to test whether transducer size helps to increase the signal strength. Preliminary tests indicated that the new design was successful in minimizing the cross talk (signal traveling to the receiver through the pipe wall) experienced earlier. This was a significant achievement in the development process. Attempts to identify and filter out this signal from the measured data were fairly successful based on the fact that the velocity of sound through steel and water is different in magnitude. Figure 5 shows the PVDF array design. Figure 6 shows the PVDF array cross section as installed on pipeline. A block diagram of the prototype flow meter is shown in Figure 7.

Laboratory Facilities at ORE

A laboratory facility was developed at ORE consisting of a 1.2-m- (4-ft-) diameter, 0.22-mm- (3/4-in.-) wall vertical steel pipe (Figures 8-10). The pipe can be filled with water and simulates no-flow conditions; however, it cannot generate any flow velocity. Transducers can be mounted externally on both sides of this pipe and tests can be conducted. An example of output is shown in Figure 11.

A few tests were conducted by creating air bubbles in laboratory pipe to simulate the effect of suspended sediment. It was found that a small number of large bubbles did not hamper the measurement; however, a large number of small bubbles made the flow meter unoperational. It was also important to ensure that the signal detection and processing algorithms were stable in the presence of rapidly changing signal levels, as would be expected in the field.

¹ R. H. Lyon Corporation Memorandum to F. C. Lowell at ORE, 15 August 1991, "Externally Mounted Acoustic Flow Meter Design"

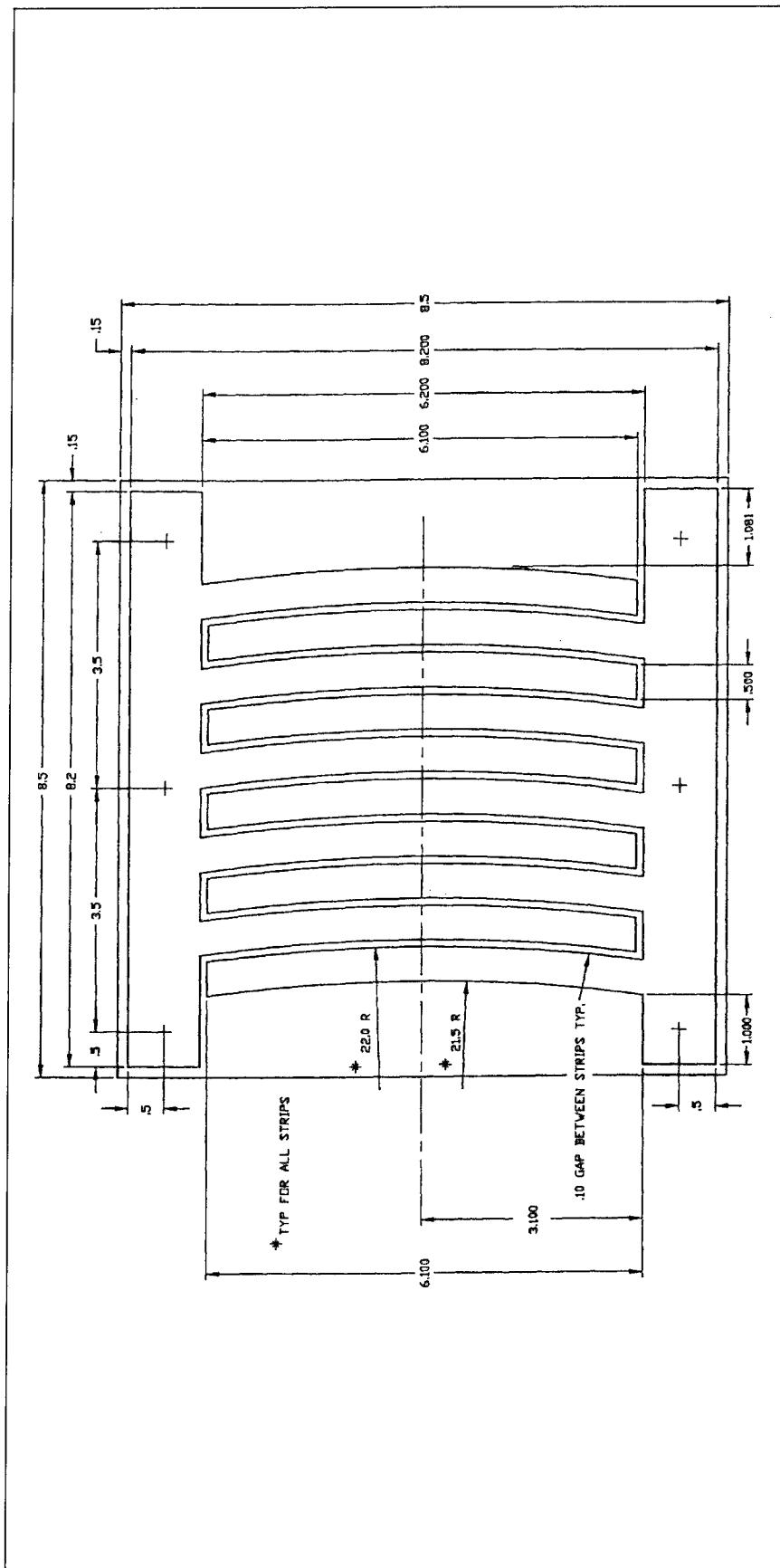


Figure 5. Layout of PVDF transducer array. All dimensions are in inches. To convert to millimeters, multiply by 25.4

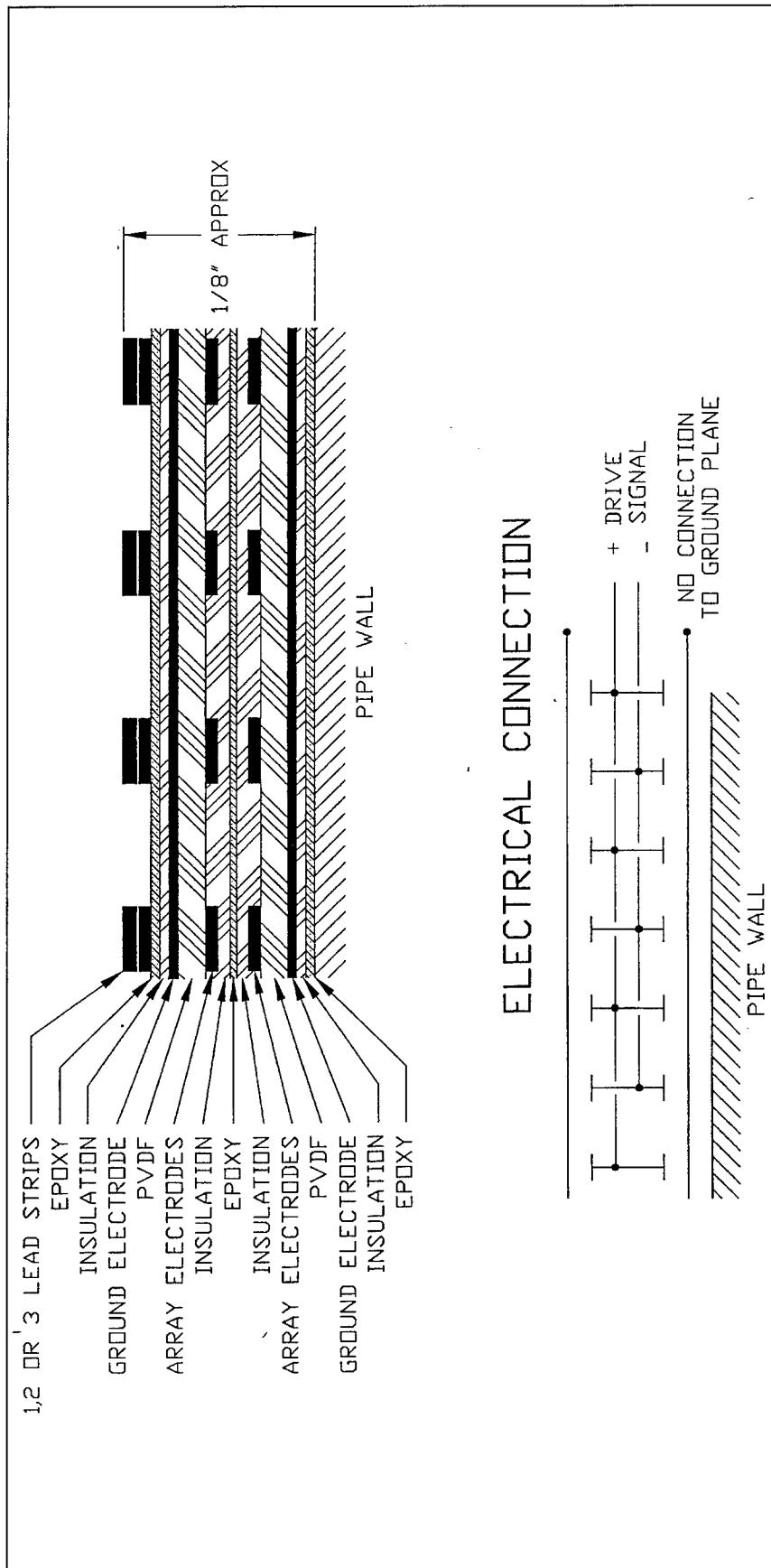


Figure 6. Typical PVDF array cross section. All dimensions are in inches. To convert to millimeters, multiply by 25.4

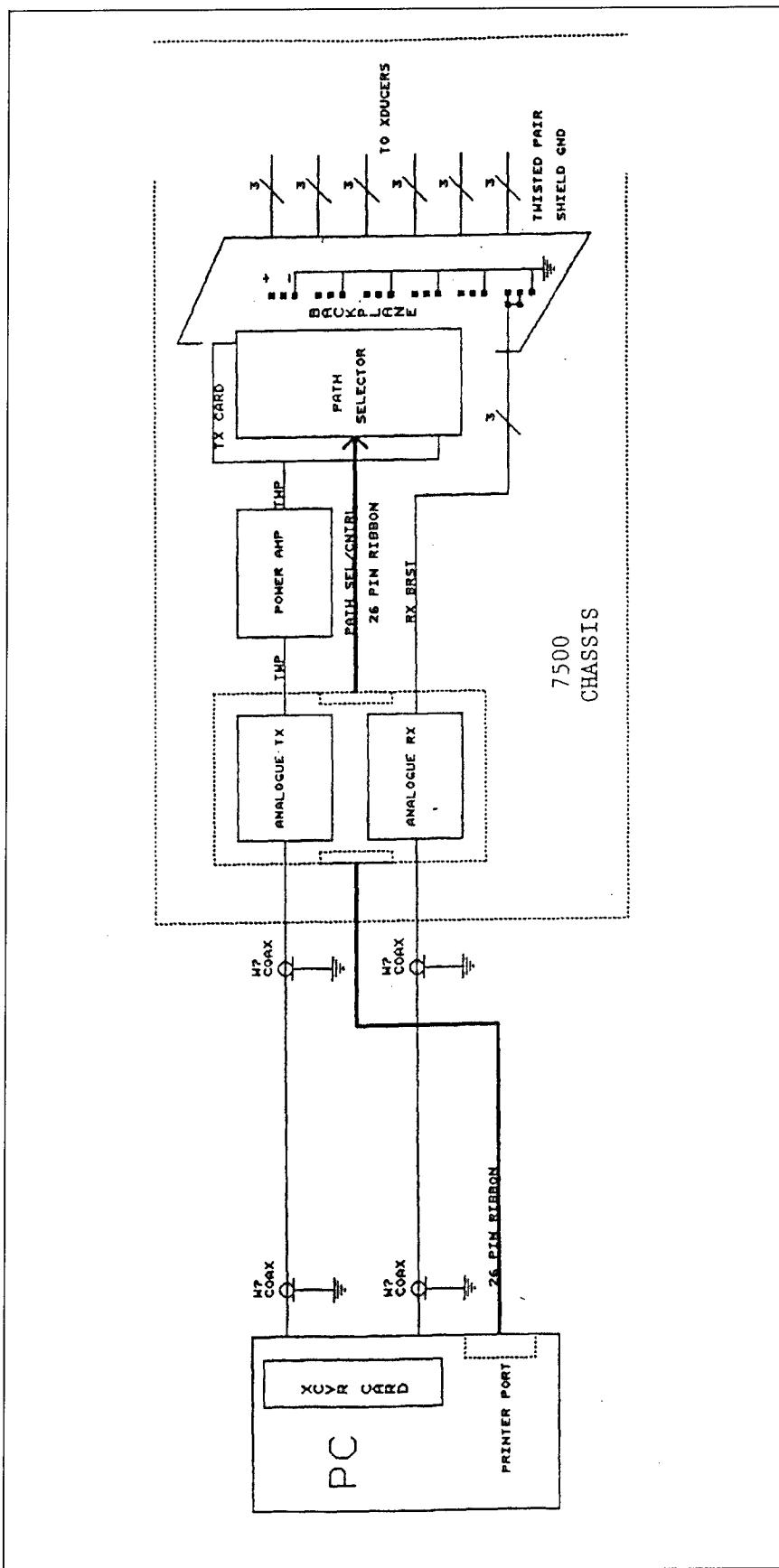


Figure 7. Block diagram of prototype flow meter



Figure 8. Testing and calibration tank

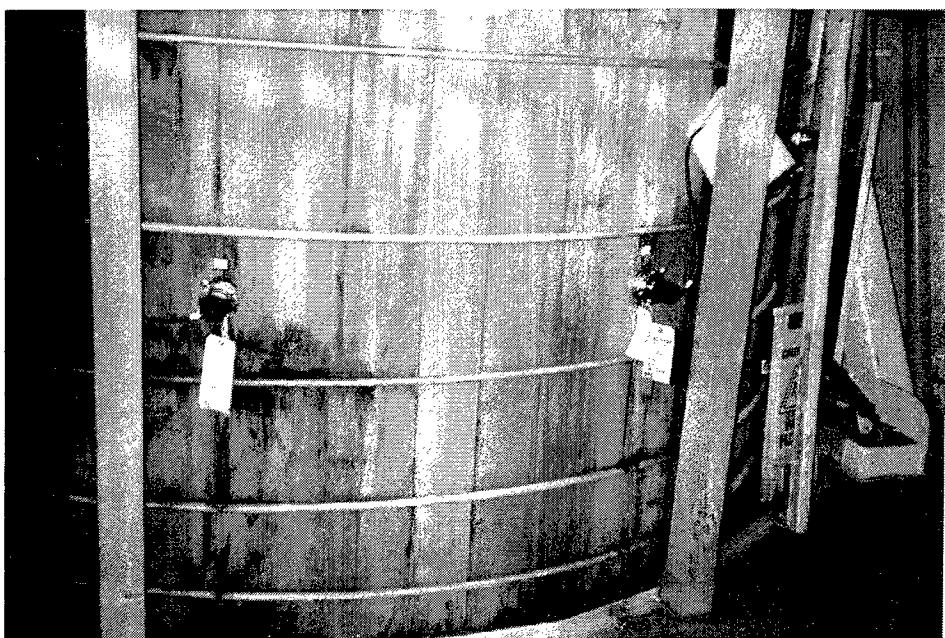


Figure 9. Closeup of testing and calibration tank



Figure 10. Steel tank for testing clamp-on type transducers

Other Test Facilities

In addition to the test facilities at ORE, the following facilities were used:

- a. Alden Research Laboratory at Holden, MA.
- b. Field test facilities at Niagara Mohawk Power Station, Colton, NY.
- c. Field test facilities on the dredge *Wheeler* in Venice, LA.

These are described later in the report.

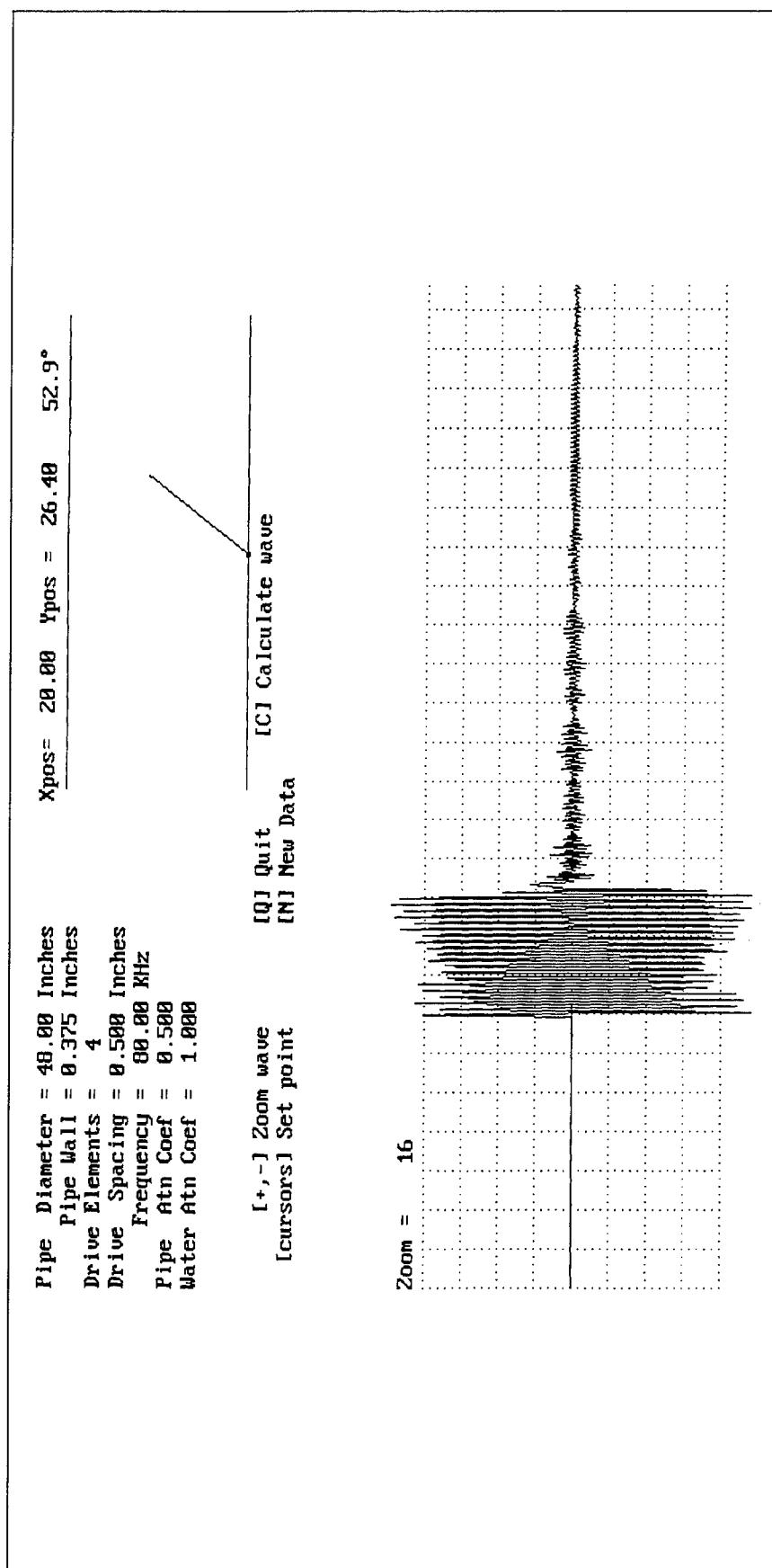


Figure 11. Output of test result at ORE facility. To convert dimensions given in inches to millimeters, multiply by 25.4

3 Research and Development Introduction

Need For a New Flow Meter

In the late 1970's WES conducted research to evaluate performance of two commercially available flow meters, the ultrasonic noise flow meter and the acoustic Doppler flow meter. The results are reported by Hanes, Downing, and Beach (1980). Both these flow meters were designed for measuring flow velocity in a pipe carrying sediment-laden water. Of the two types, the ultrasonic noise flow meter has generally not been widely accepted. The other meter, an acoustic Doppler flow meter, has the following limitations:

- a. A Doppler flow meter operates by detecting the frequency shift of an acoustic signal reflected from moving particles in a flowing liquid. A major limitation of the Doppler technique is that the source of the reflected signals depends on the distribution of particles in the fluid. When the concentration of suspended solids is low, the sound penetrates further into the fluid and hence higher velocity is reported. When the suspended solids content is high, a lower velocity is reported. The distance from which the majority of the backscattered energy comes depends on the density of scatterers. For example, in relatively clean water such as is encountered in water supply systems, the energy may be scattered from all sections of the acoustically ensonified volume, thus providing an average Doppler shift across the pipe diameter. However, when the density of scatterers is high, such as occurs in aerated or silt-laden water, the energy is scattered and absorbed very close to the pipe wall, thus representing only the velocity near the pipe wall. Since there is no way to calculate the depth of penetration of the acoustic signal into the scattering medium, the accuracy suffers, because the output is strongly dependent on the density of scatterers, as well as the velocity.
- b. The meter has no way of distinguishing the source of the received signals, and the meter calibration varies with the sediment density.

- c. The meter is extremely sensitive to crossflow, i.e., velocities that are not parallel to the pipe center line.
- d. Doppler meter accuracy is susceptible to changes in temperature and density of fluid, as these affect the angle between the acoustic path and the pipe center line.

It was concluded in Hanes, Downing, and Beach (1980) that the Doppler meter had high reliability but its accuracy was lower than that of a clamp-on diametrical path travel time meter. It was further pointed out that the clamp-on travel time meter will not operate satisfactorily in a high-sediment environment because of signal attenuation due to the sediment. The report recommended that a continuing Research and Development effort should be maintained by the Corps to find and evaluate techniques with potential to improve productivity of dredges. The present CPAR project was an effort in that direction.

New Acoustic Flow Meter

ORE International, through its Accusonic Division, has been a leader in the design, manufacture, and installation of high-accuracy, differential-travel time acoustic flow meters for river, aqueduct, and pipeline flow rate measurement since the early 1970s. A number of these units have been supplied to the private industry and to the U.S. Army Corps of Engineers and installed in the Columbia and Missouri River systems.

The high absolute accuracy of these flowmeters, up to ± 0.5 percent of flow rate, is achieved through the use of multiple, chordal acoustic paths. Multiple paths, usually two to four, when installed according to standard numerical integration locations, can produce very high accuracies because the flow rate output can be made virtually independent of the velocity profile. These accuracies are not possible with systems that use diametrical paths, such as the clamp-on Doppler and travel time flowmeters described in the following paragraphs. Because of their accuracy, multiple-path acoustic flow meters are the only acoustic meters accepted under U.S. and international standards for acceptance testing of hydroelectric turbines and other demanding applications. Schematic representation of a two-path flow meter and a three-path flow meter is shown in Figure 12.

Up until now, the installation of multiple-path chordal differential travel time flow meter transducers has entailed either dewatering the pipe and carrying out expensive and time-consuming onsite installation, or else supplying a costly and cumbersome separate spool piece with the transducers already in place. These drawbacks have limited their use in applications where high accuracy would otherwise be of great value.

Clamp-on flow meters based on existing technology fall into two general types: the clamp-on Doppler flow meter and the diametrical

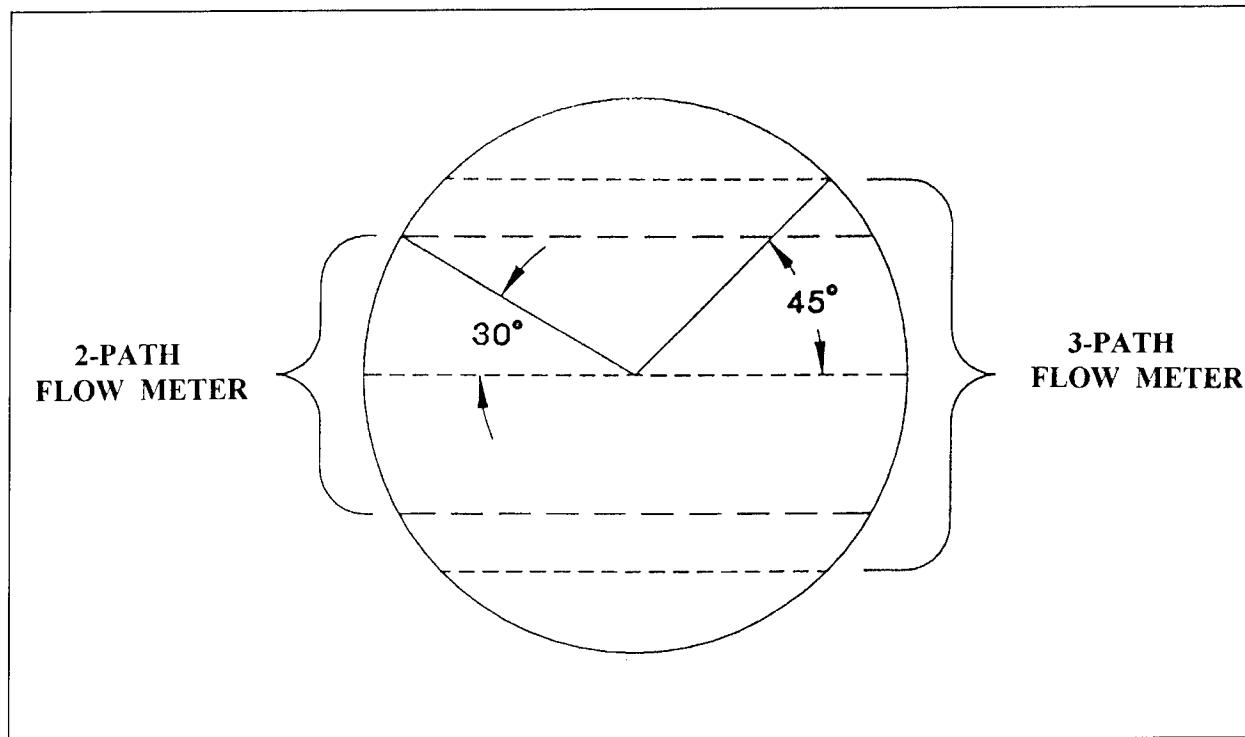


Figure 12. Schematic representation of two- and three-path flow meter (to convert degrees to radians, multiply by 0.0175)

differential travel time meter. Both these meters have severe shortcomings. They require a straight length of about 10 to 100 times the pipe diameter for a fully developed flow profile. If this is not available, additional errors and nonlinearities are introduced in the flow meter output.

Single (and crossed multiple diametrical) path differential travel time clamp-on meters representing the current state of the art suffer from their own set of accuracy and operational limitations. These result from the relatively steep path angle, typically 1.2 rad (70 deg) from the pipeline center line, which results in a very high sensitivity to nonaxial flow velocities, and the inability to use multiple chordal paths, which is necessary to provide proper integration of the velocity profile in the pipeline as flow rate, temperature, pipe roughness, and solid fraction change. Furthermore, the operating frequency is so high that acoustic attenuation limits the maximum sediment load and/or path length for useful applications.

The clamp-on differential travel time flow meter is also limited by the lack of signal strength, which results from having to send sound signal through steel pipe wall twice with accompanying severe acoustic mismatch. This makes present-day "clamp-ons" unsuitable for flow measurement in acoustically lossy fluids such as aerated and silt/sand-laden water. Schematic representation of an acoustic signal traveling through steel-water-steel path along with the mathematical relationships associated with the travel paths are given in Appendix A.

The limitation of the travel time differential flow meter was overcome by using a combination of high signal levels (large directional transducer arrays), low frequency (100 versus 1,000 kHz for low attenuation in sediment), and the capabilities of a digital signal processor technology to overcome the high attenuation in the dredge slurry. The transducer and data acquisition system are shown in Figures 13-15.

System Accuracy of Acoustic Flow Meter

It was necessary to conduct an analysis showing the integration accuracy differences to be expected for different numbers of acoustic paths. This was produced by ORE in various forms several times over the last few years for their standard flow meters. One of these analyses is given in this section. This was prepared for a presentation to the USBR. It discusses the limitations of a one-path clamp-on compared to the two- and four-path intrusive design.

The purpose of this section is to explain the differences in accuracy and performance between the Accusonic two-path to eight-path chordal flow meter systems and the crossed clamp-on bounce path approach. The clamp-on method is simpler to install and maintain than the Accusonic system with its wetted transducers. The issue is installed system accuracy. There are four basic contributors to the error in any acoustic flow meter:

- a. Acoustic path velocity errors, including errors resulting from crossflow.



Figure 13. Close-up of new transducer

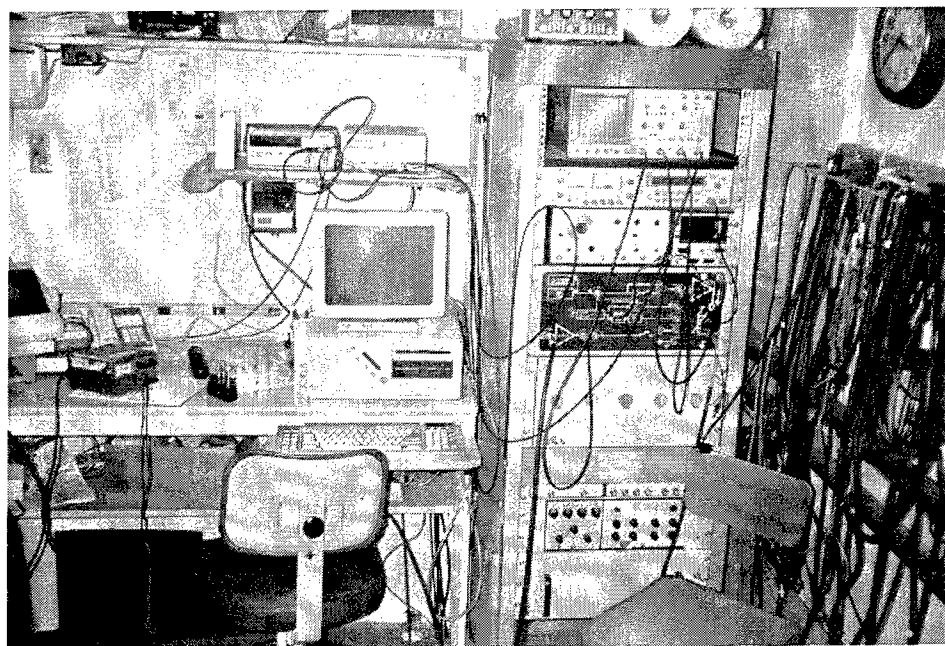


Figure 14. Hardware and software development unit

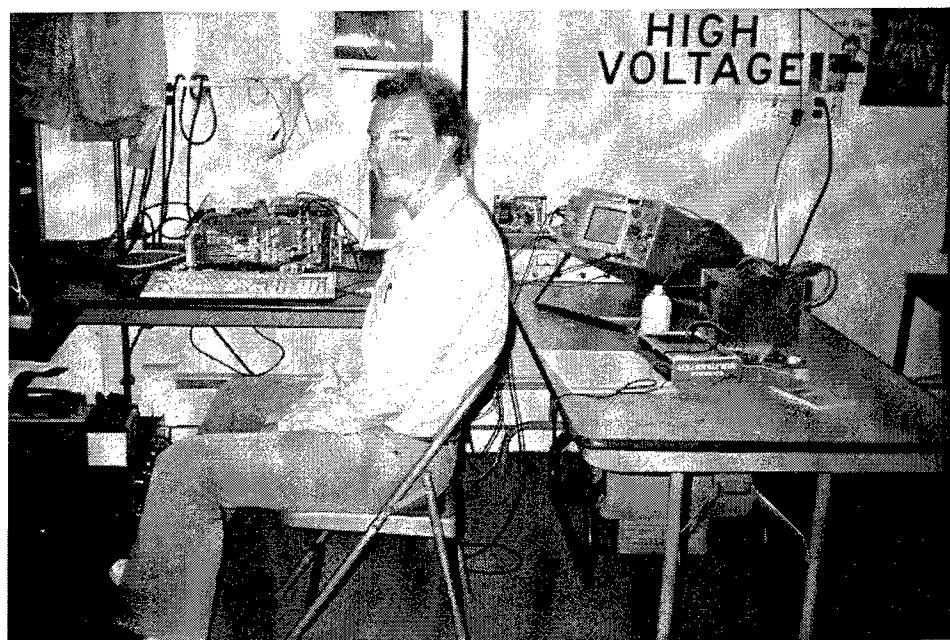


Figure 15. Data processing hardware

- b. Integration error, caused by variations in profile and nonsymmetrical profiles.
- c. Pipe cross-section errors.
- d. Electronic/processing errors.

It was important to the USBR to install acoustic flow meters without wet calibration, and a long-term stability was required. It was therefore important to analyze these error sources, and compare them for both flow meter types. In order to compare the crossed bounce path clamp-on flow meter path configuration to that used by Accusonic, it was assumed that errors under items *c* and *d* were negligible.

The bounce path approach is limited to relatively smooth (steel with no rust) interiors. Of course, concrete-jacketed and/or -lined pipes are not suitable at all, and there may be problems with corrosion-resistant ("tar") coatings and/or material buildup on the inside of the pipe interfering with acoustic propagation through the pipe wall or acoustic reflection in bounce path installations.

Path Errors

Path length resulting from "dry" calibration or "wet" measurements of each path

In the case of Accusonic (wetter transducer) path length with no bounce, use of a tape measure is simple, easy, and highly accurate. Typical path length error contribution is ± 0.03 percent. For the clamp-on path length with bounce, use of a tape measure is more difficult because the bounce point must be determined first. Path length is calculated based on measured pipe inside diameter, or measured acoustic travel time and estimated sound velocity. Error contribution is unknown, but the order of magnitude is comparable to that achieved by the direct measurements used by Accusonic.

Path angle

In the case of Accusonic (wetted transducer), path angle is measured with a theodolite for highest accuracy, or it can be calculated using upstream/downstream distances and measured diameter of pipe. Typical path angle error contribution is ± 0.1 percent. For the clamp-on path angle with bounce, diameter (preferably from inside) and distance between transducers are measured. Also, wall thickness must be known, and it is necessary to devise some way to calculate actual path through the wall to account for refraction at the transducer/steel and steel/water

interfaces. According to ORE calculations, if water temperature is not taken into account, there is an additional error of about 2 percent per 5.5°C (10°F).

Crossflow

Single-path Accusonic crossflow. A single path in an 0.8-rad (45 deg) Accusonic flow meter has a basic sensitivity to crossflow of about 1.7 percent per degree of crossflow angle. Normally, this is corrected by using crossed paths where necessary. This correction is excellent, as shown in numerous laboratory tests conducted at the Alden Research Laboratory and field tests sponsored by EPRI.

Clamp-on crossflow with bounce. The clamp-on bounce path can partially correct for crossflow in many situations. However, the correction is not as good as with Accusonic style crossed paths for two reasons:

- a. The two paths are not at the same location. In general, the crossflow component varies axially along the pipe. Two "paths" that are "crossed" upstream and downstream of each other will not provide as good crossflow correction as a pair that actually cross in the middle of the pipe. Accusonic, Westinghouse, and other manufacturers do this when accurate crossflow correction is required.
- b. Due to the extremely steep path angle inherent in the clamp-on approach, each path is much more sensitive to crossflow. This sensitivity is about 5 percent per degree, which is about three times worse than the Accusonic 0.8-rad (45-deg) path.

An example of where bounce path crossflow correction would probably be less than optimum would be near an upstream elbow, where the crossflow component is varying rapidly as the water moves away from the elbow. This situation is frequently encountered in actual installations. Only a carefully conceived test series in a hydraulic calibration laboratory would show the meter's sensitivity to this type of velocity profile.

Integration Errors

An acoustic path measures the average downstream component of liquid velocity along the path. Assuming that there is no crossflow, the velocity measured along the path can be extremely accurate; however, in the case of a diametrical single-path meter, the meter output will in general be in error because the velocity profile is not uniform. The average (path) velocity measured times the pipe cross-section area does not equal the actual flow rate. Imagine the acoustic path being broken up into equal length sections. For accurate flow measurement each section should be weighted according to the area it represents (Figure 16). In this case each section is

an annulus whose area decreases as the path approaches the center of the pipe. Therefore, in a typical case where the velocity is higher in the center of the pipe, the single-path meter assigns too much flow to these higher velocity but smaller area annuli, thus overestimating the flow rate. This is why single-path flow meters typically have a correction factor of about -4 percent for large "smooth" pipes up to -10 percent for small "rough" pipes, and about -25 percent for a parabolic (laminar) velocity profile.

Variable and unknown velocity profiles often pose a problem in the design of measurement. Every textbook on hydraulics shows the classical

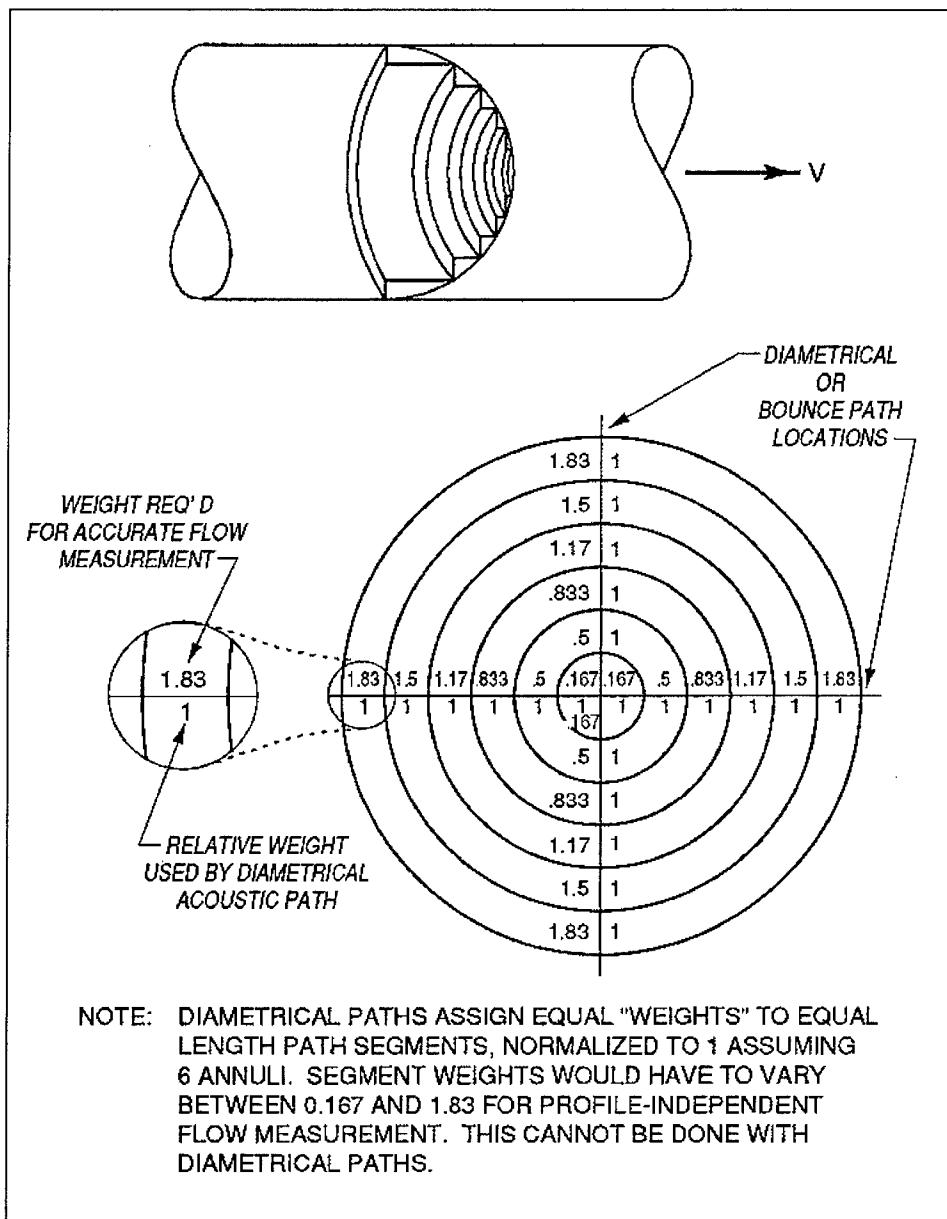


Figure 16. Weights of sections for accurate flow measurement

laminar flow velocity profile as a symmetrical parabolic shape. Perhaps it would be possible to achieve this with a relatively viscous fluid in a small pipe at low velocity. However, it is necessary to have a Reynolds number below 2000 and about 200 diameters of straight, smooth piping upstream in order to achieve the laminar flow profile. In real life, particularly with water flowing in "normal" size pipes, 1-10 meters in diameter, laminar flow will not be possible, because Reynolds numbers are way above the turbulent transition, usually between 100,000 and 50,000,000. The turbulent profile varies with Reynolds number, pipe wall roughness, and distance from upstream bends, transitions, valves, etc.

Fully developed turbulent flow profiles also require a pipe length of at least 10 to 100 diameters to develop, and they differ from laminar flow profiles because the velocity profile is dependent on Reynolds number and pipe surface roughness. Tests were conducted at BIF, Inc., to compare results obtained with a single diametrical path and a two-chordal-path Accusonic flow meter. It was noticed during the tests that 100 diameters of straight smooth pipe upstream is not nearly long enough to achieve fully developed turbulent flow in a 152-mm- (6-in.-) diameter pipe, with Reynolds numbers up to about 500,000.

It is important to understand that in most applications, usually there are upstream elbows, transitions, valves, pumps and other objects within the 100- to 200-diameter distance upstream. At present the turbulent velocity profile cannot be accurately predicted and even if it was accurately measured, or calibrated during installation, it would change with temperature, time (roughness, rust corrosion, fouling, etc.), and flow rate.

The four-path chordal system produced by Accusonic is inherently insensitive to velocity profile variation, as has been proven in repeated field and laboratory tests, as well as computer simulations.

One way to think about the multiple diametrical bounce path approach is to think of it as "symmetrifying" a nonsymmetrical velocity distribution. Given enough diametrical paths, any distorted profile will be perfectly "symmetrified" and will be effectively converted to a symmetrical velocity distribution inside its processor. However, this does not mean that the meter factor versus Reynolds number curves shown in Figures 17 and 18 can then be applied. There is no reason to expect that the symmetrified profile will obediently look like the classical fully developed turbulent flow profile for the corresponding Reynolds number that Figures 17 and 18 show.

When considering the clamp-on bounce path approach, even with two or more bounce paths, the important point to understand is that this is a "diametrical" system, and that no matter how many diametrical paths are installed, the inherent sensitivity to profile variation is still going to be there because all the paths make the same "mistake" and there is no way that the meter can correct for this. There will, however, be a reduction in the error due to unsymmetrical velocity profile, so a multiple-path

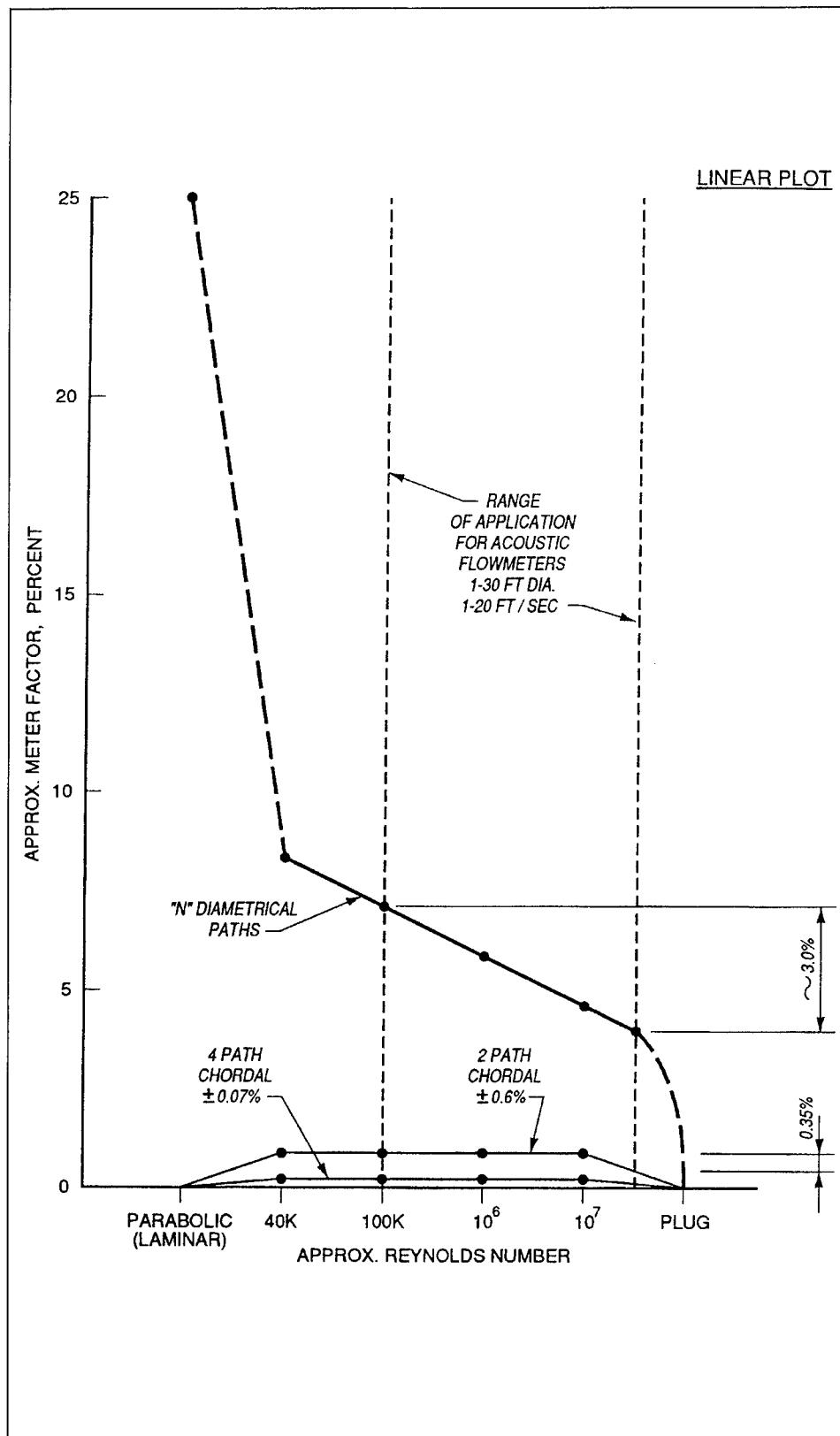


Figure 17. Meter factor versus Reynolds number curves (linear plot) (to convert feet to meters, multiply by 0.3048)

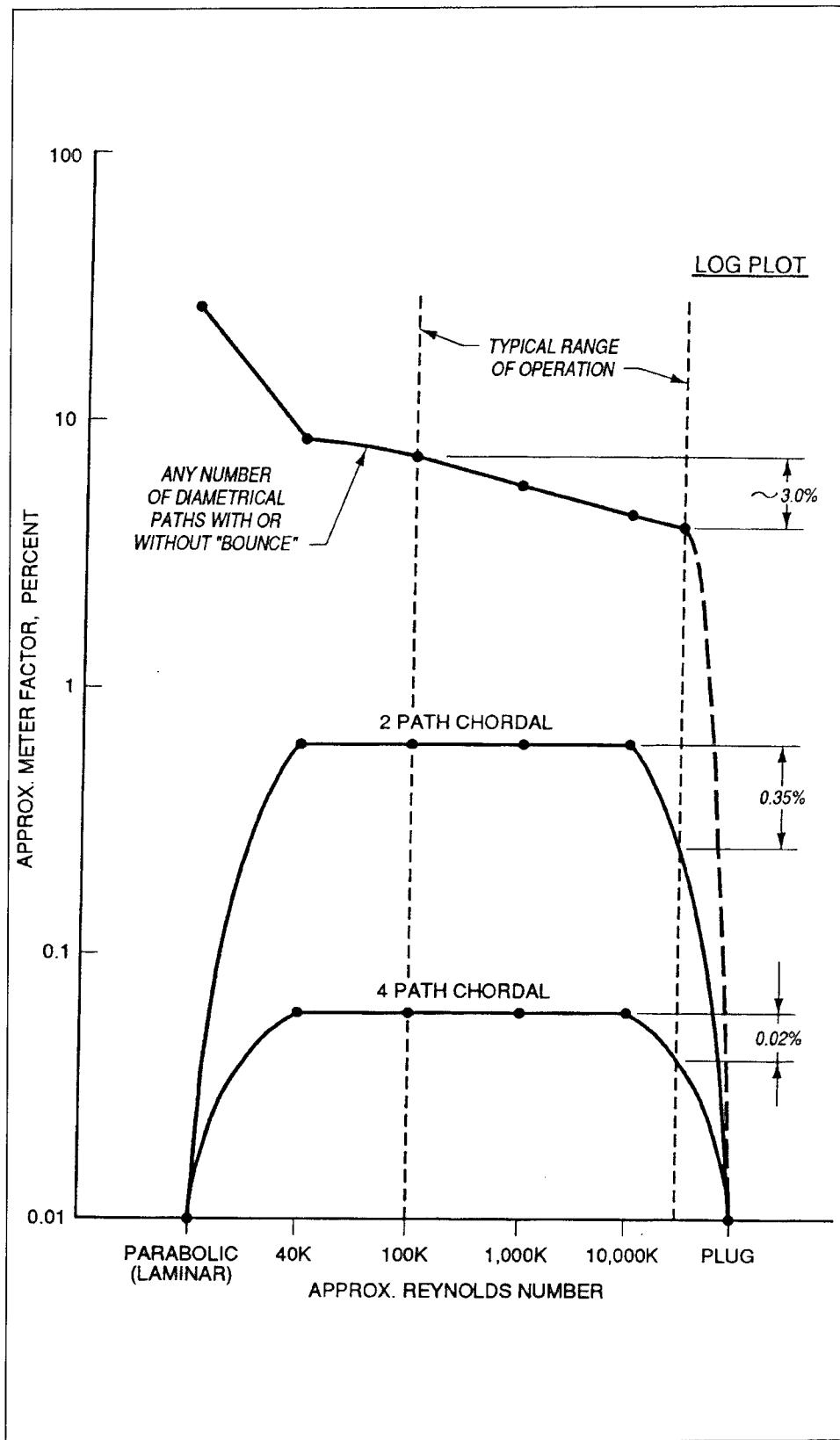


Figure 18. Meter factor versus Reynolds number curves (log plot)

diametrical system will be more accurate than a single-path diametrical system if the velocity profile is unsymmetrical, but it is inherently incapable of achieving the accuracy of a chordal system. This conclusion is also supported by the acoustic flow meter standard prepared by ASME (1993) and the draft PTC-18 Standard.

Summary of Error Sensitivity

If it is determined that the dual bounce path clamp-on approach might meet the project requirements, the manufacturer should be asked to test the proposed meter in a hydraulic laboratory at several locations and orientations immediately downstream from an elbow. This procedure was adopted before the ORE flow meter was declared acceptable by the USBR and the California Department of Water Resources (DWR).

It is recommended that a test program closely following the test program suggested by DWR be prepared in order to facilitate performance comparisons between the two systems. The test program may also be specifically designed to show the worst-case susceptibility of the Accusonic meter to nonsymmetrical, distorted, and crossflow conditions.

Tests should be designed to reflect actual field performance capabilities. For a clamp-on system a factory-measured spool piece should not be used. The manufacturer should make all measurements by simulating the field conditions.

The results obtained by ORE on error sensitivity versus type of flow meter are presented in Table 1. Such data should be a matter of public record. It is only fair that a manufacturer proposing to install equipment in competition with others and claiming comparable accuracy should be required to perform similar tests, and allow the competitors to review the results.

Research Needs For New Flow Meter

ORE had demonstrated technical feasibility for this type of flow meter by establishing acoustic propagation diagonally across a 1.2-m- (4-ft-) diameter steel pipe section filled with water.

The product idea would not have arisen without the availability of large, low-cost transducers made possible by the newest transducer technology, PVDF, and the work of R. H. Lyon Corporation personnel. A possible flow meter configuration for this application is shown in Figure 19 (ORE Drawing No. 7400-BE-0733). A patent was applied for this concept

Table 1
Error Sensitivity versus Type of Acoustic Flow Meter

Error Source	One Path Clamp-on (Diametrical)	Bounce Path Crossed Clamp-on (Diametrical)	Two-Path Chordal	Four-Path Chordal	Eight-Path Crossed Chordal
As-Built Path Error and Temperature Effect	Not as good as wetted transducer installation. Also may be temperature sensitive (Approx. 2° per 5.5 °C (10 °F))	GOOD	GOOD	GOOD	GOOD
Crossflow Sensitivity	BAD 5 percent/Degree	GOOD <1 percent/Degree?	FAIR 1.7 percent/Degree	FAIR 1.7 percent/Degree	EXCELLENT <<1 percent/Degree
Nonsymmetrical Flow Profile Sensitivity	Very Bad ~10 percent	The more paths the better, assume <0.5 percent	GOOD ~1 percent	EXCELLENT ~1 percent	EXCELLENT ~1 percent
Symmetrical Flow Profile Sensitivity	POOR ~±1.2 percent	POOR ~±1.2 percent	GOOD ±0.5 percent	EXCELLENT ~1 percent	EXCELLENT ~1 percent

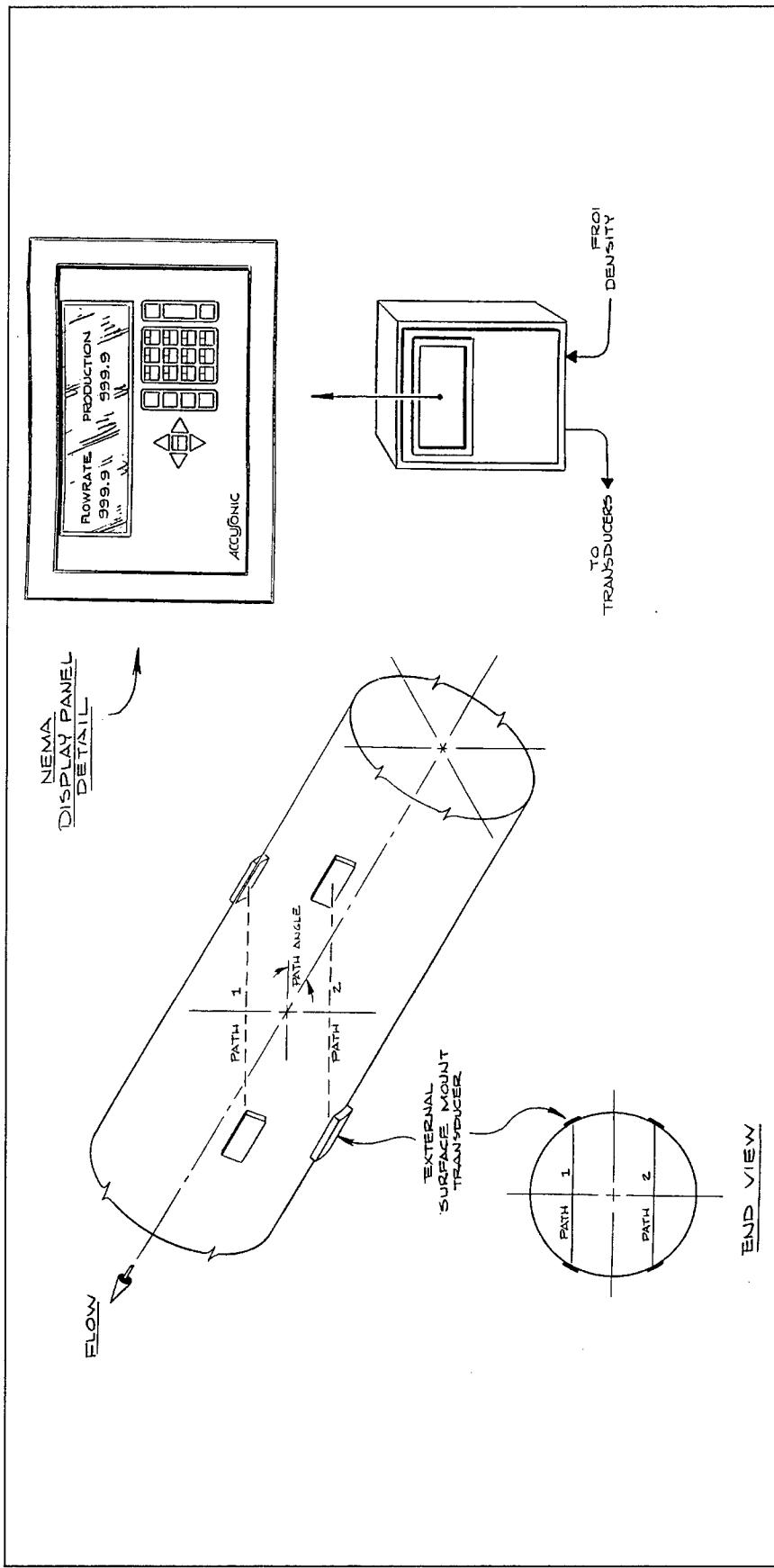


Figure 19. Initial proposal of flow meter configuration (ORE Drg. 7400-BE-0733)

in October 1991, and Patent Number 5,228,347 was issued on July 20, 1993 (Appendix B).

The main uncertainty was in the "envelope" of operation possible with this type of product. The system tradeoffs had to be evaluated relating to frequency of operation, signal bandwidth, signal beam width, pipe size, wall thickness, number of acoustic paths, and accuracy. These are all interrelated, and all answers were not readily apparent until the initial phases of this program were completed. For example, the tests conducted were run at 100 kHz, with a bandwidth of about 10 kHz, a pipe wall thickness of 9.5 mm (0.38 in.), and a pipe 1.2 m (4 ft) in diameter. For flow measurement in a smaller pipe, such as used on suction dredges, a higher frequency would normally be expected (except for the fact that the sediment in the water tends to attenuate these higher frequencies).

Normally, a flow meter is required to operate both at high and relatively low fluid velocities. In the dredging environment high accuracy is required when velocities are relatively high, in the 4.6- (15-) to 7.6-m/sec (25-ft/sec) range. The new flow meter offers a potential advantage for this application because it allows operation at lower frequencies, which are more compatible with silt-laden water. The devices currently available in market have the following disadvantages:

- a. Relatively steep path angle resulting in high sensitivity to nonaxial flow velocity.
- b. Inadequate signal strength.
- c. Nonavailability of multiple paths.

The following research needs were identified for the new development:

- a. Establish tradeoffs between transducer array size, mounting configuration and performance, particularly frequency, signal strength, and useful signal bandwidth. All of these relate to the ultimate timing resolution achievable with the design.
- b. Determine the optimal transmitted signal coding for maximum time resolution and signal-to-noise ratio.
- c. Fabricate a prototype system for testing in the field. This would probably consist of a personal computer (PC) with the capability of data acquisition and off-line signal processing.
- d. Conduct field tests under controlled conditions, to determine the performance of the system under varying conditions of silt load, pipe size and flow rates.

Developmental Problems

The following problems were encountered:

- a. It is easier to generate and measure an acoustic signal from the inner surface of a pipe than to propagate the signal through the pipe wall. When the signal is produced outside a steel pipe, it is necessary to have a much stronger source in order to overcome the signal losses caused by the velocity of sound differences (impedance mismatch) between the steel pipe wall and the water.
- b. Acoustic signals also propagate along the inside of the pipe walls, causing multiple signal arrivals at the opposite transducer. This crosstalk limits the maximum usable length of the signal pulse.
- c. For relatively small diameter pipes, such as those used on dredges, the path length is relatively small. Hence the accuracy of time measurement needs to be very high in order to achieve reasonable accuracy in flow measurement.
- d. The relatively high concentration of suspended sediment and air bubbles expected in dredge pipes will cause attenuation of the acoustic signals.
- e. Only two companies in the USA produce PVDF. The transducer strips available in 152- by 12.7-mm (6-by 0.5-in.) size (among other sizes) were tested for determining their suitability in forming arrays of various shapes and transmitting the required signals.

Development Stages and Achievements

Although this CPAR-Cooperative Research and Development Agreement (CRDA) between ORE and WES started officially in March 1993, work in connection with the development of an acoustic clamp-on type flow meter was underway at the ORE during 1989. Important preliminary work was done by ORE before the CPAR project started in 1993. Several stages of development were required. Important project tasks are as follows:

- a. Selection of material suitable for use as transducer.
- b. Testing of selected material for its properties.
- c. Optimization of size and thickness (28, 52, and 104 microns) of PVDF strips.
- d. Optimization of shape of the array.

- e. Determination of range of grazing angles for different path locations.
- f. Development of hardware and software for prototype system.
- g. Development of a simulator for testing hardware.
- h. Testing at ORE facility.
- i. Development of data acquisition software.
- j. Development of data analysis software.
- k. Field test with sediment-free water.
- l. Field test with sediment-laden water.
- m. Production of prototype unit.
- n. Production of marketing unit.
- o. Marketing and technology transfer.

Work on these and other related items continued over 4 years from 1993 through 1996. Several tasks were done in parallel. In view of the complexities of the research and development works, the stages are described in Chapter 4 in chronological order. The research and development stage described in each subsection does not necessarily denote completion of a task during that period. Each 3-month period starting from January 1993 has been considered as a stage for the convenience of reporting. The achievements made during the 4 years 1993 to 1996 are described under these stages.

Work Done By Subcontractor

In 1989, ORE International retained the services of Robert H. Lyon, Professor of Acoustics, Massachusetts Institute of Technology, Cambridge, MA, through his consulting firm, R. H. Lyon Corporation, to assist in exploring an entirely new approach to clamp-on flow meter technology. This investigation eventually focused on a new transducer material, PVDF, which is low in cost and which could be manufactured in large arrays that conform to the pipe exterior. It was believed that by using this material, and suitable signal generation and pulse compression techniques, multiple-path accuracy levels might be achieved and signal strength losses overcome. An additional advantage of the new approach is that it is an inherently lower frequency system. Thus it is potentially suitable for applications involving measurement of silty or air-laden fluids.

The following tasks were to be performed by the subcontractor:

- a. *Definition of desired source distribution.* This consisted of development of the mathematical relationship between the force distribution on the outer pipe wall and the velocity distribution on the inner wall as functions of frequency over the range of interest of pipe material properties and pipe thickness.
- b. *Array driver design.* This included developing an analytical model that relates the array geometry, amplitude taper, and phasing to the desired force distribution.
- c. *Drive signal definition.* This included activities related to specification of the signal wave form and its envelope.

The following was performed by Lyon Corporation:

- a. Preliminary mathematical analysis of pressure patterns on the inner and outer surfaces of pipe was completed, and the results were submitted to ORE.
- b. The theoretical development consisted of determining the shape of the acoustic beam at the transmission and receiver ends of a circular pipe. This was achieved for the signal passing through the center of the pipe as well as along a chord.
- c. Several computer simulations were performed in the laboratory to determine the optimum configuration of transducer strips for the best signal transmission. Based on these, it was recommended that a “shaded array” configuration might work by reducing the crosstalk expected to be caused by the side lobes of the transmitted signal.
- d. The main problem ORE worked on was to try different shapes of array. Individual elements of transducers were cut and arranged in the required configuration for shaded arrays. This was not completely satisfactory. Hence trials were also taken with various configurations without cutting the elements, but rather cutting the lead mass backing. It was found that although the shaded array was better than the originally tested rectangular (unshaded) array, the overall efficiency of transmission was lower. During all these trials, R. H. Lyon Corporation provided results of computer simulations for different configurations prior to their testing.

In August 1991, R. H. Lyon Corporation submitted to ORE a detailed report (Appendix C) giving the experimental results on the design of an externally mountable acoustic flow meter. In brief, the performance of the PVDF transducer when installed on the exterior of a 1.2-m- (4-ft-) diameter, 9.5-mm- (0.38-in.-) thick pipe section, was as expected, and therefore proved suitable for flow rate measurement. Another report was submitted by R. H. Lyon on 27 May 1994 on further results of sensitivity analysis of transducer performance (Appendix D).

4 Research and Development

Stage 1

Prior to this CPAR project, ORE had been working to develop a clamp-on acoustic flow meter. This developmental work was continued under the CPAR project, which started officially on 1 March 1993. Work was centered on the following tasks:

- a. System design tradeoffs:
 - (1) Array element drive sequencing.
 - (2) Optimum frequency of operation.
- b. Prototype transducer array design:
 - (1) Geometry.
 - (2) Phasing.
- c. Prototype (off-line) processor design:
 - (1) Transmitter(s).
 - (2) Receiver(s).
 - (3) Data acquisition system.
 - (4) Processing software.

The following were accomplished:

- a. Acoustic paths were installed on the 1.2-m- (4-ft-) diameter by 9.5-mm- (0.38-in.-) wall water-filled pipe section at the ORE test facility. These included a diametrical path, a two-path (± 0.2 rad (30 deg)) chordal and a four-path chordal. The last path represents the most difficult path geometry for this type of array. Due to

receipt of several defective PVDF strips from the vendor, the four-path was not operational.

- b. The data acquisition system consisted of a PC with a high-speed (10 MHz) analog-to-digital sampling capability. It was used to capture data transmitted along the acoustic paths. The PC also controlled a transmitter designed to allow any frequency or wave shape to be applied to the transmitting arrays.
- c. Software was written to generate any desired signals for the transmitter and to determine the time of received signal zero crossings, which is used to measure the acoustic travel time.
- d. A meeting was held on 31 March 1993 to discuss the progress of the research and a future plan of action.
- e. At that time, the capability to transmit and receive signals on the diametrical and 0.5-rad (30-deg) paths, with acceptable signal-to-noise ratios for operation in clean water was demonstrated.

Stage 2

- Accomplishments during this stage included the following:

- a. R. H. Lyon personnel wrote generalized software to compute the pressure distribution on the inside of the pipe for an arbitrary pipe diameter and path position. The corresponding pressure distribution on the outside of the pipe was also determined. Shaded arrays were simulated using these programs, enabling design of the element pattern on the outside of the pipe.
- b. This information enabled ORE to fabricate the first "optimized" array, using shaded elements, on a diameter with a 0.79-rad (45-deg) path angle. ORE also received patterns for other path positions, but there were significant problems with the PVDF vendor, who was unable to provide a material that had reliable contacts between the factory supplied leads and the PVDF. This problem was resolved, and a large shipment of PVDF strips was arranged. It took several trials before ORE was able to successfully fabricate the array.
- c. Modifications to the transmitters and receivers were continued to support operation of the new arrays.
- d. The signal levels received using the optimized array were lower in magnitude than the original "rectangular" arrays built by Lyon and rebuilt by ORE.

Stage 3

In July 1993 ORE received a patent for the externally mounted arrays. During July and August 1993, problems with the PVDF transducers were resolved and the required material was obtained for ongoing testing.

It was noticed that some of the earlier arrays were not achieving optimum coupling to the pipe section because the lead backing was not flat enough. A method was developed for testing the array after it was installed to ensure proper coupling to the tank.

It was discovered that the thickness of the PVDF film affected signal strength, contrary to what was anticipated. The PVDF strips were 152 mm long by 19 mm wide (6 in. long by 0.75 in. wide), folded in half longitudinally in order to reduce their width, which also increased the amount of signal generated. The film thickness itself was not affecting performance, but rather the array capacitance and resistivity of the electrodes applied to the element surfaces. The thinner material, 27 microns thick, had so much capacitance that the array resistance limited the current to the array, reducing its output. The thicker materials, initially 52 microns and then 104 microns thick, had one-fourth the capacitance and therefore much less signal attenuation in the conductive electrode films.

Extensive tests were conducted with the original "rectangular" arrays and the newer "optimized," or "shaded" arrays developed by R. H. Lyon Corporation. These tests showed that the optimized arrays did not provide significant improvement over the original rectangular design. This was somewhat surprising to ORE and Lyon personnel, because improved signal strength and reduced crosstalk with the optimized arrays were anticipated.

The improved performance achieved with the rectangular arrays made it clear that building flow meters with two and perhaps three paths with adequate signal strength would be possible. The lack of improvement from the shaded arrays did not cause concern. Furthermore, since an inherent property of shaded arrays was a slower rise time, using them was not warranted unless an improvement in other characteristics was noticed. By improving the array fabrication methods, it was possible to achieve ample signal strength for flow meter operation, even on the chordal path locations ($\pm 0.5\text{-rad}$ (30-deg) offset, 0.8-rad (45-deg) path angle). This meant that a chordal design was definitely feasible. It was not clear whether greater path separations, corresponding to more acoustic paths, would be possible. A limited amount of signal was observed at $\pm 0.8\text{-rad}$ (45-deg) path locations, perhaps enough for clean water operation with three paths in larger pipes. A $\pm 0.9\text{-rad}$ (54-deg) array, corresponding to a four-path chordal configuration, was not successful.

It was decided that the shaded array development would not be pursued and ORE would concentrate on rectangular arrays. The fact that no

improvement was achieved with the shaded array was valuable information in itself.

System design tradeoffs

An understanding of the tradeoffs and limitations of the proposed approach was developed during this period and a highly satisfactory set of system components and techniques was evolved based on past experience and theoretical knowledge. These are summarized in the following paragraphs.

Transmitted signal coding. The transmitted signal would be a high-power 100- to 1,000-W continuous wave burst of about 50 to 100 kHz.

Sampling requirements. The received signal would be sampled at 10 MHz. This was a higher frequency than the ultimate production system would require, but it ensured that any subtle effects that might not be so obvious at a lower sample rate were not missed.

Processing requirements. The received signal would be digitized at the above-mentioned 10-MHz rate. The times of the positive and negative going zero crossings would be measured and averaged. At that time the ultimate method that would be used for cycle determination had not been determined. Based on the laboratory measurements made to date it appeared that a timing resolution of better than 10 nanoseconds could be achieved. This was more than sufficient for these purposes, and was comparable with what was being achieved with standard flow meter designs.

Array element drive sequencing. The array would be driven with a simple “push-pull” balanced drive using a high-power (hundreds of watts), low-impedance amplifier. The array was very capacitive, and electrical tuning was not possible because of the requirement for low differential time offset. It was not clear whether an even simpler switching (square wave output) amplifier could be used.

Optimum frequency of operation. Initially it was assumed that 100 kHz would be a suitable frequency. Based on an excellent zero offset performance, it could be possible to go to lower frequencies, perhaps as low as 25-50 kHz. This would improve the signal strength in larger, thicker walled penstocks. It might also be possible to use lower frequencies in the dredging application, but the pulse length has to be kept shorter than the propagation time between transmitting and receiving arrays in the steel pipe wall.

Prototype transducer array design

Geometry. Surprisingly, after all the studies conducted by R. H. Lyon and ORE, the original array geometry was very close to optimum. The

reason for this was not totally clear, but the optimized shaded arrays, which were carefully computer modeled by Lyon and fabricated by ORE on the test pipe section, did not reduce the crosstalk, or the signal that propagates between transmitting and receiving transducer arrays in the pipe wall. Since this signal interferes with the direct in-water path, it limits the pulse length if it cannot be eliminated.

Phasing. Complicated phasing of the array was not required. This was an advantage because it simplified the design of the system. As mentioned in the previous section, the array was driven in a simple push-pull fashion, and the signal strength at the receiver was more than adequate.

Mounting methods. After the shape and element geometry of the array were determined, work proceeded on fabrication of prototype transducers. This required the generation of master artwork, followed by fabrication in the PVDF vendor's plant.

Prototype (off-line) processor design

Extensive modifications were made to both hardware and software. A total of three different transmitters were used with extensive modification of the software.

Stage 4

During October 1993, tests were performed in the 1.2-m-(4-ft-) diameter pipe section "tank" in order to determine the best method for detecting the acoustic pulse in the presence of signal distortion caused by compressed air injected into the tank, using single paths located at the diametrical and dual path locations on the pipe section.

The compressed air was intended to simulate the air and sediment conditions that might exist in a dredge pipe when pump cavitation and seal leakage may result in significant amounts of air in the slurry stream. Of course, this is not a consideration in a hydroelectric application, but a robust method was needed of detecting the correct zero crossing of the received signal for travel time determination when signals are not at optimum strength, as when aligning the arrays during installation. At that time a maximum pipe wall thickness capability of 12.7 mm (0.5 in.) is anticipated.

Several methods were tested, including the use of a phase reversal in the middle of the pulse. It was determined that a reliable method was to use the known characteristics of the pulse shape in order to determine the pulse presence and to identify the correct zero crossing when it arrived at the receive array. This method was implemented in the prototype system software.

The transmitter was rebuilt in order to increase the available signal strength. The transmitter was capable of driving almost any load impedance at a 500-V level over a frequency range of 50-150 kHz.

A complete eight-path working prototype system was built inside a single enclosure controlled from a PC.

The first prototype arrays were ordered from AMP Sensors, along with a steel rule die for forming the lead backing.

ORE was concerned that the supplier of arrays might not be interested in the relatively low level of business that even a highly successful flow meter development might generate compared with their other businesses, which include everything from naval submarine conformal sonar arrays to running shoe heel flashers. Hence on 3 November 1993, Mr. Lowell visited AMP Sensors to discuss the optimum material type and thickness available, and to ascertain their interest in small accounts in their overall business plan. AMP assured that they were indeed interested in ORE business and that they were setting up a second profit center dedicated to the lower production levels. In addition, they indicated that past problems with timely delivery and quality control were over, and the takeover by AMP Sensors was complete.

On 17 November 1993, ORE received the first prototype arrays. The steel rule die was received on the 19th. Using the die, it was very simple to form the lead backing required for each array.

During the next several weeks ORE completed the prototype system hardware and software, and tested the new arrays. An immediate problem was that the arrays did not have a sufficient thickness of insulation on their exterior surfaces, and electrical breakdown was preventing operational tests. The remaining two arrays were returned to AMP on 14 December. It was gratifying to note, however, that the arrays were relatively easy to install, now that they had been reduced to two pieces rather than about 20 per array required during the earlier tests.

Pending return of the arrays, work commenced on building a simulator for evaluation of the system performance. Block diagrams of the prototype system and simulator were prepared. About 50 percent of the simulator hardware was completed.

Alden Laboratory Test

Before the design was modified and the flow meter tested in the field, it was considered necessary to test its performance in a laboratory. The test was conducted at the Alden Research Laboratory, Holden, MA. Twenty-five units of "integrated" one-piece arrays were ordered from AMP Sensors, Inc. Pending delivery of the integrated arrays, ORE

ordered 40 more PVDF strips for further testing on the tank at ORE, and for a hydraulic calibration test at Alden Research Laboratory on a 914-mm-(36-in.-) diameter 9.5-mm-(0.38-in.-) thick steel pipe.

The facilities at Alden Research Laboratory consisted of a 1.2-m³/sec-(44-ft³/sec-) capacity diesel-electric pump and a 45,359.2-kg-(100,000-lb-) capacity weigh tank and associated 914-mm-(36-in.-) diameter piping, together capable of providing an accuracy better than 0.25 percent of flow rate. The maximum velocity achievable was about 21 m/sec (7 ft/sec) in the 914-mm-(36-in.-) diameter pipe.

The test at Alden was carried out on 28 February and 1 March 1994. This test was witnessed by Dr. Gregory H. Nail of WES. After a few false starts due to leaking seals in the water pumps, successful calibration runs were performed over a 0.1- to 1.1-m³/sec (4- to 40-ft³/sec) (0.6- to 6.0-m/sec (1.9- to 19.7-ft/sec)) range. It was determined during the test that there were some software errors, which produced an offset of about 4 percent in the flow rate readings. These were corrected after the fact, and the resulting corrected calibration runs are shown in Figures 20 and 21. Figure 20 shows test results on a 609-mm-(24-in.-) diameter pipe, and Figure 21 shows results of tests conducted on 914-mm-(36-in.-) diameter pipe. Reference flow was determined from the precision weigh tank.

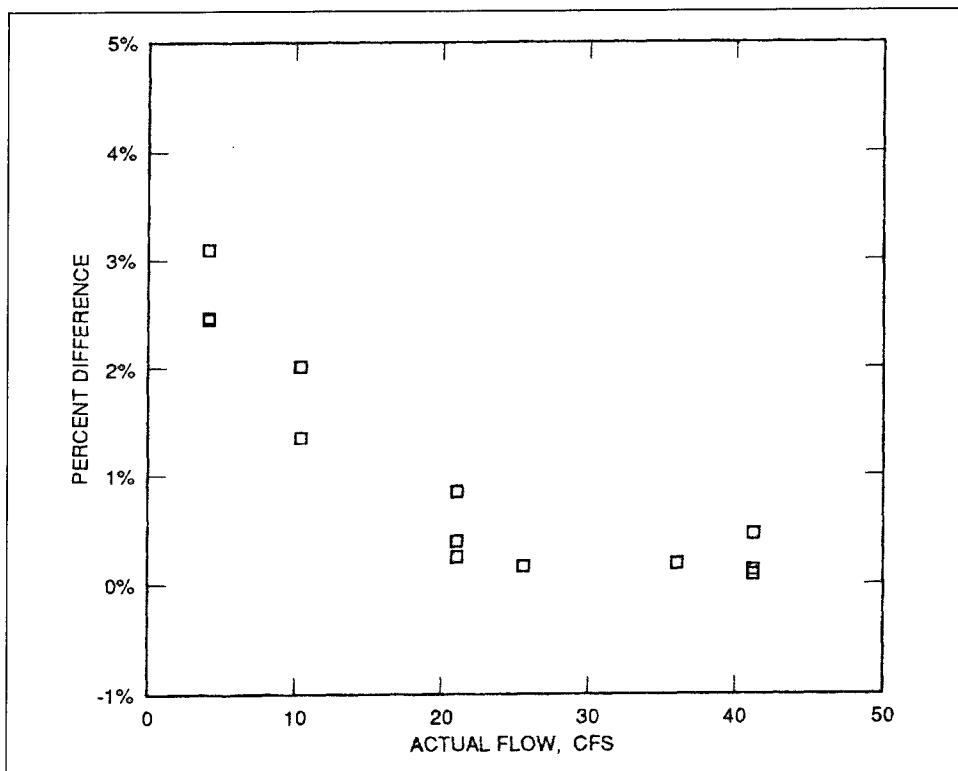


Figure 20. Flow meter calibration at Alden Research Laboratory, 609-mm-(24-in.-) diameter pipe (to convert actual flow to m³/sec, multiply by 0.0028)

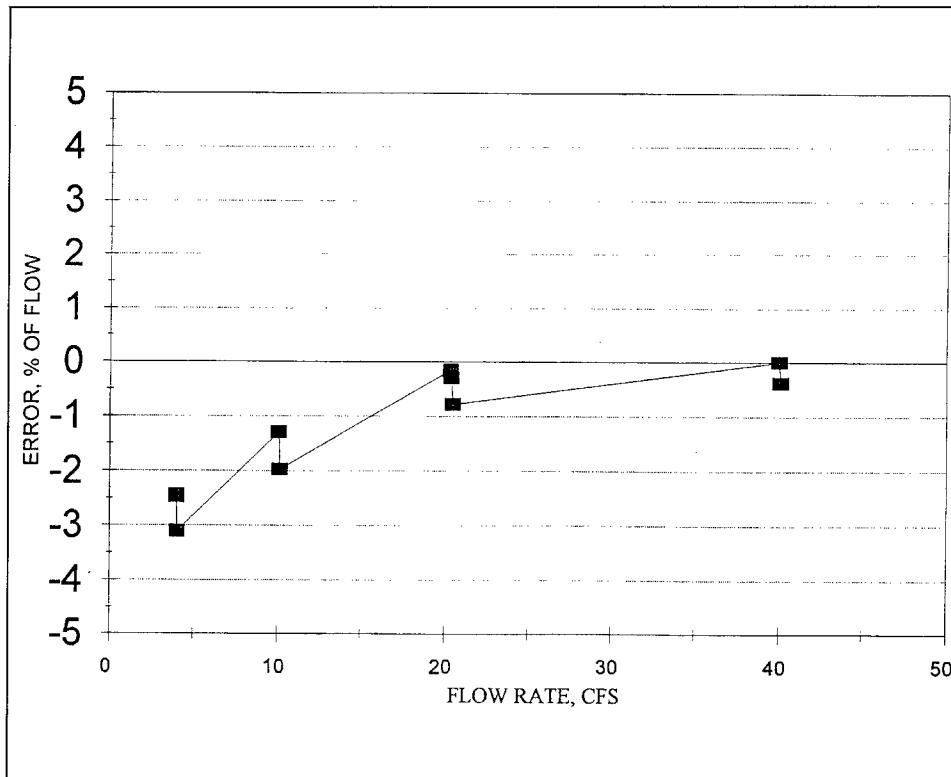


Figure 21. Test results of handmade arrays, 914-mm (36-in.) flow meter calibration (to convert flow rate to m^3/sec , multiply by 0.028)

A review of these data showed that there was still a significant error at low flows less than 0.9 m/sec (3 ft/sec). This was due in part to the use of nonidentical handmade arrays, and also partly due to the relatively low maximum flow rates which were achievable in the laboratory environment in a 914-mm (36-in.) pipe. This low flow error is characteristic of what is called a zero offset: the small zero flow output becomes a larger fraction of the measured flow at low flow magnitudes.

The following were the conclusions of the Alden Laboratory test:

- a. The handmade arrays used eight folded 104-micron-thick PVDF strips, for a total thickness of 208 microns of PVDF (not including insulation and electrode thicknesses), and array dimensions of about 101 by 152 mm (4 by 6 in.). Tests were conducted at an operating frequency of 73 kHz, with a pulse length of 0.3 msec. The acoustic signal was sampled at 10 MHz. The test results were very satisfactory. They showed that "dry calibration" is possible using this type of array, and the corrected data showed an accuracy approaching 1/2 percent of flow rate at the higher flows above $0.6 \text{ m}^3/\text{sec}$ ($20 \text{ ft}^3/\text{sec}$) (0.9 m/sec (3 ft/sec)). This accuracy was expected to hold for much higher flows also.

- b. The crosstalk, or the acoustic signals traveling between transmitter and receiver around the pipe rather than through the water, was not a problem even in this smaller diameter pipe.

Stage 5

The results of the Alden Laboratory test were presented to personnel at WES on 7 March 1994 as a part of a general presentation on the progress of the project.

The simulator was completed, and it was then used to verify the signal cycle detection algorithm used in the prototype system software.

By mid-March 1994, the integrated PVDF arrays were delivered by AMP. While there were no problems with voltage breakdown as had been experienced with the prototype integrated arrays, initial tests using a single thickness of 104 microns on a diametrical path were not encouraging. Several days were spent trying to determine the difference between the performance of the integrated arrays and the individual strips used previously. It was finally determined that the total thickness of the PVDF strips, which were folded double to reduce their width, was also performing the important function of increasing the mechanical compliance (in thickness) of the array element, which, when combined with the lead backing strips, was "tuning" the array mechanically. Doubling up the integrated arrays by epoxying two arrays together back to back to simulate the folded condition served the same function; and by increasing the thickness of lead backing, it was possible to duplicate the performance of the handmade arrays.

Further testing of the performance of individual strips operating straight across the pipe, to eliminate the steering with frequency, allowed ORE to determine the frequency response of arrays of differing PVDF and lead backing thickness.

The coding optimization studies were conducted using design data provided under contract with R. H. Lyon Corporation, which showed that there was little if anything to be gained by using complex coding and/or complex array designs. At the same time, while these designs were being tested at ORE, it was found that timing resolution and signal-to-noise ratio requirements could be met and exceeded using a simpler zero-crossing timing method and nonshaded rectangular array and pulse shaping.

The prototype system design, electronics, and software were completed.

Stage 6

Considerable work was done by the subcontractor, R. H. Lyon Corporation. ORE officials visited them on 5 April 1994 and held discussions on the development. The subcontractor submitted computer model data to ORE for examination. Additional discussions were held on 28 June when a Lyon engineer visited ORE. On 30 June, updated model data were received from Lyon Corporation. ORE engineers visited another PVDF vendor, and tested samples of their material. These tests were unproductive.

Time was spent trying to understand the mechanics of the individual PVDF strips used in the flow meter transducer arrays. The problem ORE encountered was that the acoustic output of the strips did not change predictably when the thickness of the PVDF and the lead backing was varied. This was particularly true when operating in the 60- to 100-kHz range because losses in the pipe wall are lower at lower frequencies as are the losses anticipated in the dredge slurry. The performance of the arrays was repeatable, indicating that once a workable array element was built, it should be possible to make more units of the same reliably.

R. H. Lyon Corporation was retained to model the mechanical behavior of the pipe-epoxy-PVDF-epoxy-lead sandwich used when constructing the arrays. The models were tested on a pipe section, and initially there was very poor agreement between model and real world.

On 28 June, ORE demonstrated the test results on PVDF strips to one of the engineers from R. H. Lyon, who was able to identify some potential problems with the computer model they had been working with. On 30 July he produced some results indicating that the arrays in the low-frequency range (60-100 kHz) could produce better results if the element spacing and grazing angle between the acoustic beam and the pipe wall were adjusted to avoid undesirable coupling between the pipe wall resonance and the array resonance. A preliminary test performed on one of the existing arrays on the tank confirmed that the resonant frequency of the array elements could be lowered successfully if the grazing angle between the acoustic path and the tank wall was reduced, as is the case with the 0.5-rad (30-deg) chordal path. These tests were continued.

Enough was learned about the behavior of the arrays at higher frequencies to build working arrays for the field and other tests in the 100- to 130-kHz range. On the electronic front, the hardware design for the production digital printed circuit board was completed.

Stage 7

The major accomplishment during this period was a better understanding of the operation of the PVDF arrays. The PVDF array problem

turned out to be a resonance within the pipe wall whose frequency varied with grazing angle. This prevented the arrays from "tuning up" properly on the diametrical paths tested. This had not been understood earlier, when it had been assumed that the pipe wall resonated only in the thickness mode, and therefore the frequency would be independent of grazing angle.

The solution turned out to be that at the smaller grazing angles experienced with chordal paths, it was necessary to operate at a lower frequency, and conversely, it was necessary to use a higher frequency for the diametrical paths. Up to that time the diametrical paths had been built and tested with the arrays, in the belief that they would be easier to understand. Most of the first order of 25 arrays were used doing these tests. Fortunately the array geometry ORE worked with was already designed for a lower frequency than the individual strips which they had been building into arrays, and therefore the arrays on the chordal paths could be operated satisfactorily.

At this point, the basic array structure was to epoxy two arrays back to back and operate them electrically in parallel (for lower electrical impedance) and mechanically in series, for a lower mechanical resonance frequency. Two or three 1.3-mm- (0.05-in.-) thick lead strips were epoxied to the outside of each array element to tune it mechanically to the operating frequency, which was in the 60- to 80-kHz range.

Having achieved satisfactory array performance on chordal paths, ORE placed an order with AMP Sensors for 50 more arrays on 21 July, this time with a 52-micron thickness. The 6-week delivery time for these arrays meant that the field test could not be scheduled until September. The arrays were tested during the first week of September, and no difference was found between these new 52-micron arrays and the old 104-micron ones tested. The contractor supplied arrays with the wrong thickness. They agreed to build new arrays, but in the meantime the thick arrays had to be used for the field tests.

Colton Field Test

It was necessary to identify a hydroelectric project site where a section of a large water-carrying pipe was fully exposed and easily accessible for mounting the transducers. The pipe wall was not to be more than 9.5 mm (0.38 in.) thick for testing the present design. It was necessary to scrape the paint off a small area (about 304 by 304 mm (12 by 12 in.) of the pipe where transducers needed to be pasted. Permission of the project authorities was essential for this specific requirement. Also their cooperation was needed in conducting the test. ORE considered a site on White River in Vermont, where a 2.4-m- (8-ft-) diameter exposed pipe was available; however, it turned out that there were several disadvantages to the use of

this site, including the lack of a flow reference to determine the accuracy of the flow meter. Hence the proposal did not materialize.

An ideal site was then identified for the field test at a hydroelectric plant in New York State operated by the Niagara Mohawk Power Company. The 3.9-m- (13-ft-) diameter pipeline at the site was nearly horizontal, was totally exposed, and was 9.5 mm (0.38 in.) thick. Permission to test the meter on the pipe was obtained, and the consent of site officials was also obtained for cooperation during the test by varying flow conditions and making measurements using their equipment.

The Colton site was selected based on the following advantages:

- a. An exposed steel pipe was available for easy installation.
- b. The pipe diameter was 4.1 m (13.5 ft), adequately large for testing.
- c. Site was easily accessible by road.
- d. Electric supply was available for installation and testing.
- e. The wall thickness of steel pipe was 9.5 mm (0.38 in.), thin enough for transmission of the signal.
- f. Project authorities agreed to run different discharges through the penstock during tests.
- g. Permission was given to scrape off the paint from outer surface of pipe for transducer attachment.
- h. A four-path chordal flow meter (Model 7500) installed by ORE on the same pipe was available for comparison of results.
- i. The site was relatively close to ORE (9-hr drive).

The field test was conducted during 19-23 September 1994. A total of five pairs of externally mounted transducer arrays were installed on the pipe (Figures 22 and 23) about 15.2 m (50 ft) downstream of the previously installed flow meter (Accusonic Model 7500). The arrays were installed to provide the following configurations:

- a. A single 0.8-rad- (45-deg-) diametrical path. This was the easiest configuration to install and produced the largest signal strength. The arrays for this path were built from folded 52-micron PVDF strips rather than the arrays, as this had consistently produced the largest signal strength in diametrical paths during tests at ORE.
- b. Two 0.5-rad (30-deg) chordal paths, also at a 0.8-rad (45-deg) plane angle. These were built using the 104-micron PVDF arrays.



Figure 22. Installation of transducer on penstock at Colton

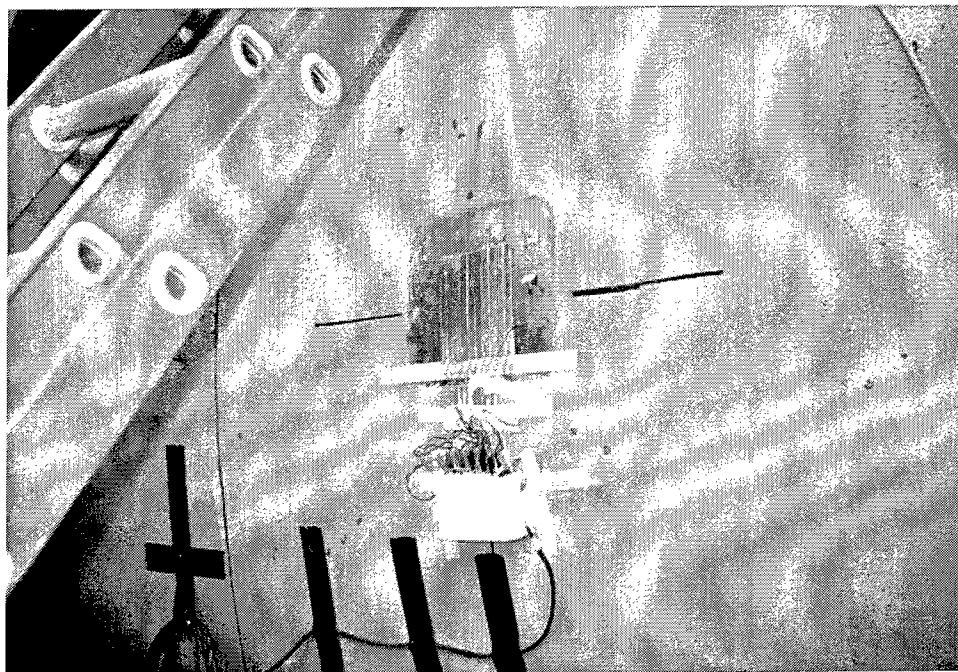


Figure 23. Closeup of transducer installed on penstock

- c. Two 0.8-rad (45-deg) chordal paths, also at an 0.8-rad (45-deg) plane angle. These were installed to allow the testing of a three-path meter, which uses the diametrical path for the third path. Based on the accuracy analysis and simulation results conducted during the early development of the 7000 series flow meters at ORE, a three-path meter was found to be almost as accurate as a four-path. It has been already determined from tests at ORE that the ± 0.9 -rad (54-deg) (outer) four-path locations did not work satisfactorily on the test tank.

The objective of the Colton field test was to evaluate the signal strengths obtained with the various path configurations, and to compare the measured flow rates with those obtained with the already available flow meter. The flow rate was varied during the tests from zero to $4.7 \text{ m}^3/\text{sec}$ ($166 \text{ ft}^3/\text{sec}$). A comparison of measurements is shown in Figure 24. Reference flow was measured using a four-path intrusive flow meter (Accusonic Model 7500). Data points show measurements made with the new externally mounted flow meter.

The following conclusions of tests were drawn:

- a. The two-path configuration provided ample signal strength. The measured flow rates were within a few percent of the flow meter Model 7500.

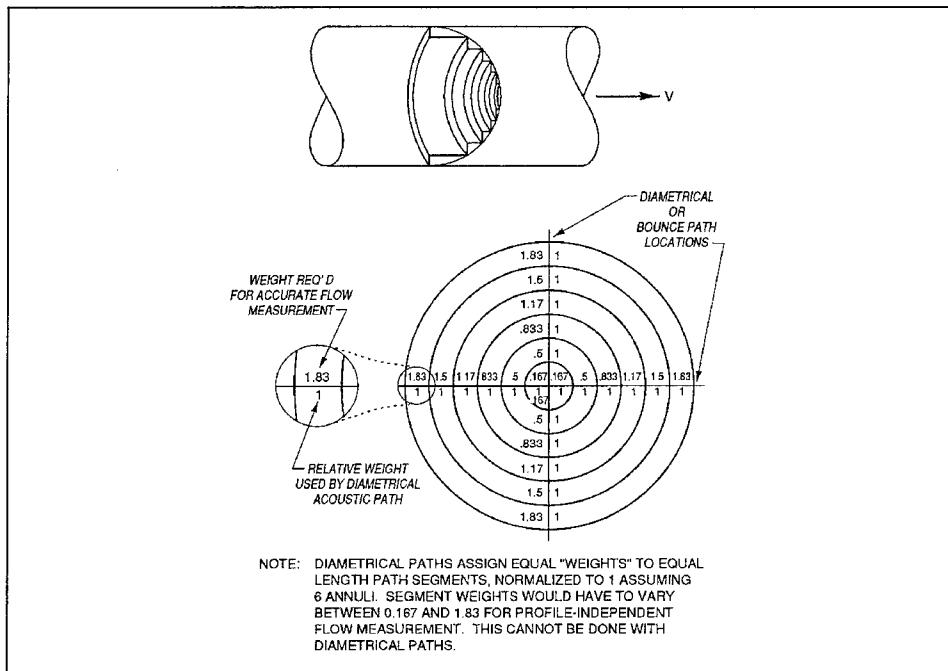


Figure 24. Comparison of results obtained by intrusive and externally mounted flow meters, two-path flow meter versus 7500, 4.1-m (13.5-ft) diameter at Colton, NY. Flow rates given in ft^3/sec . To convert to m^3/sec , multiply by 0.028

- b. The three-path flow meter provided barely adequate signal strength. The velocities measured with the outer two signal paths agreed well with the velocities reported by the flow meter model 7500; however, the integrated velocity was about 5 to 10 percent lower than the other measurement, probably because the Model 7500 measures velocity along the diametrical path, which is longer than the chordal length of the two-path meter.
 - c. The diametrical path of the new flow meter provided ample signal strength; however, the velocity measured was about 10 percent lower than the Model 7500 value. The reason for this needs to be investigated.

Stage 8

Two major accomplishments occurred during this stage:

- a. The two-path and three-path data taken at Colton, NY, were analyzed and compared with the reference flows and velocities from the Accusonic Model 7500 flow meter at the site.
 - (1) All the acoustic paths installed at Colton, NY, operated satisfactorily as far as acoustic signal strength was concerned. In fact, there was 10 dB of excess signal on the $\pm 0.5\text{-rad}$ (30-deg) (two-path) arrays, which means that for clean water, pipeline wall thicknesses of up to 12.7 mm (0.5 in.) could probably be handled without further increases in signal strength.
 - (2) The velocities measured on the 0.5-and 0.8-rad (30- and 45-deg) arrays agreed well with the velocities measured by the reference meter, and the flows calculated on the two-path meter also agreed well with the reference meter flow measurements. However, the central diametrical path, which was one of the paths in the three-path meter, consistently read low by about 6 percent, without an explanation. The data were studied exhaustively, and researchers were unable to repeat these incorrect measurements on 1.2-m (4-ft) test pipe at the ORE facility.
 - (3) It was realized that something was wrong because two conditions had to be met for a given path to operate properly. The first was that the measured velocity of sound must be correct for the measured water temperature (and the same as the other paths), assuming that the path lengths are accurately known. This provided a quick check on the path geometry, because an incorrect velocity of sound will always mean that something is wrong with the path. The second condition was, of course, the velocity measurement. The velocity can be estimated by inspecting the other path velocities and the velocities seen on the Accusonic

Model 7500 reference meter immediately upstream. Because of the nearly ideal velocity distribution at this site, combined with the excellent agreement between the two-path configuration with the reference meter, it could be stated confidently that the velocity readings are low on the central path. For the velocity to be the observed 6 percent low (with the correct path length), then the path angle to the flow, which is the only other variable, must be in error by about 0.04 rad (2.5 deg). This is very unlikely, because the physical location of one transducer would have to be in error by about 0.5 m (1.5 ft) (given the constraint of staying on the diameter of the pipe), and moving the transducer this distance along the pipe would throw the velocity of sound way out. The electronics and software were checked extensively, and no problems were found. Therefore the cause of the discrepancy was undetermined.

b. A prototype design for a prefabricated PVDF array was tested and with minor modification it was found to be satisfactory for future tests as well as for standard production.

- (1) This design consisted of a square polyurethane cover with a 6.4-mm- (0.25-in.-) deep square cavity that fitted over the PVDF array/lead backing "sandwich," both of which are prefabricated in the shop. A 3.1-mm- (0.13-in.-) thick open cell neoprene foam pad served as a flexible spacer to fill the cavity. The cover had a 12.7-mm (0.5-in.) NPT threaded hole in the center of the back for electrical attachment.
- (2) To install the array, the desired location is determined and reference lines are made on the pipe exterior. Any paint, rust, or roughness is removed from the pipe exterior by grinding or sanding as required, and low-viscosity epoxy (Tra-Con 2114) is applied to the pipe, the array sandwich, and the perimeter of the cover. The epoxy chosen has a 1-hour pot life to allow adequate working time for several arrays to be installed with one batch of epoxy. This epoxy is also available with longer pot life. This assembly is held on the marked location while the threaded conduit hole with connecting wires protruding is connected to a small vacuum pump. Thus the cover becomes a "vacuum bag" that holds the array in place, squeezes out any bubbles in the epoxy, and provides uniform clamping force to the curved pipe exterior during the cure period. If the pipe exterior is badly pitted, a bead of very thick epoxy (3M DP-190) can be applied to the perimeter to stop air leakage during cure. About 12-24 hours later the vacuum pump is removed and electrical connections to the electronics are made after a conduit junction box is installed on the back of the array.

Stage 9

Two major accomplishments occurred during this stage:

- a. The flow meter electronics design was completed, and production prototype was mostly completed.
- b. The flow meter software was approximately 90 percent completed.
Tests were conducted in the ORE laboratory using the 1.2-m- (4-ft-) diameter pipeline section with nonflowing water.

The production prototype operated slightly better than the original PC-based prototype system tested at Alden Research Laboratory and during Colton field tests because of reduced internally generated noise, thus increasing signal margins by about 6 db.

The architecture of the flow meter is different from the original plan. It was originally intended to make this design a part of the Accusonic Model 7500 flow meter using the application software already developed and using the new transceiver design only to measure acoustic travel times. Instead, it was decided to use the extensive software capabilities of the Digital Signal Processor (DSP) module to perform the flow rate calculation, as well as handling the input/output and user interface. This allowed a smaller, simpler, and less expensive (more price-competitive) overall product. A remote digital display will be provided for the dredge operator, as well as 4-20 mA output and a 4-20 mA input from the density measuring system if it is available. The unit is packaged in a 508-mm (20-in.) high, 508-mm (20-in.) wide, and 254-mm (10-in.) deep National Electrical Manufacturers Association (NEMA)-4 enclosure. The liquid crystal display (LCD) unit is approximately 76.2 mm (3 in.) wide by 127 mm (5 in.) high by 25.4 mm (1 in.) deep. It can be located at a distance of up to 7.6 m (25 ft) from the processor.

Stage 10

The prototype production unit hardware and software were completed and were ready for field testing. It had been operating for over a month on the test tank at ORE.

ORE marketing department worked on the commercial hydro/wastewater market for the system.

Stage 11

Initial market research activities for the dredged slurry flow meter (DSF) included source identification and survey of dredging industry supply companies with products and services concerning dredged material production meter systems and related instrumentation systems. Additionally, listings of companies involved in dredge vessel manufacturing and dredging system components were compiled.

A meeting was held at WES on 15 September 1995 with Dr. T. M. Parchure and Mr. Glynn E. Banks of WES and Mr. Terry Burch from ORE. Discussion topics included the following:

- a. Identification of salient dredging engineering and technology references.
- b. Identification of points of contact within the Corps of Engineers and dredging industry.
- c. Identification of professional dredging associations.
- d. Discussion and overview of Production Meter System function and uses.
- e. Considerations for system-user interfacing and operating environments.
- f. Procurement organization (key personnel) for dredging companies.

In preparation for the test on a working dredge in New Orleans, ORE made preparations to test a 1.2-m- (4-ft-) diameter steel spool piece with a 15.9-mm (0.6-in.) wall thickness at their shop. The reason for this special test was that the externally mounted transducers are limited by the maximum pipe wall thickness that can be used, and all previous tests, including the field test at Colton, NY, last year had a wall thickness of 9.5 mm (0.38 in.). ORE analysis of signal strength at that time indicated that they could have handled a pipe wall thickness of at least 12.7 mm (0.5 in.). Therefore it was important to test a pipe section with a thicker wall that will be on the working dredge.

Performing tests at the ORE facility allowed experimentation with different array configurations in order to optimize the signal strengths. To this end ORE ordered 100 more PVDF strips (in addition to the supply of array assemblies) in order to be able to build several different arrays if required. Testing of both one- and two-path configurations was anticipated.

Regarding documentation, revisions to the artwork for the digital processing Printed Circuit Boards were finished.

Dredge Technology Corporation, Wayne, NJ, a subsidiary of IHC Holland, The Netherlands, expressed a preliminary interest in developing a partnership or original equipment manufacturer (OEM) relationship with ORE International for commercial application of the new DSF. This was to be pursued more substantively following test and evaluation of the prototype DSF on actual dredging field trials.

Stage 12

ORE procured a 1.2-m- (4-ft-) diameter by 1.8-m- (6-ft-) long spool piece for testing system operation on a 15.9-mm (0.63-in.) wall thickness pipe. Surprisingly, the signal strengths received on the 0.8-rad (45-deg) diametrical path were almost as strong as those received on the similar 9.5-mm (0.38-in.) wall pipe, which has been the test bed in the past. However, operation at the chordal two-path locations was disappointing. Hence alternate path angles had to be tested in order to determine the cause of the poor performance. Out of the installed four paths, only the diametrical path worked satisfactorily. It was necessary to determine what range of grazing angles provided adequate signal strengths.

Market research and commercialization activities for the DSF development continued with further source identification and survey of dredging industry companies providing products and services for dredged material production meters and auxiliary instrumentation. This included the listing of companies involved in dredge vessel manufacturing and dredging system components. Operational capabilities of the DSF would be better defined following test and evaluation of the prototype unit during actual dredging field trials. This would include a better determination of dredge pipe sizes and wall thickness compatible with the new transducer technology that has been under development for the prototype DSF.

Information gathering and collation continued in the following areas:

- a. Identification of dredging engineering and technology references.
- b. Ordering of several salient references and publications.
- c. Points of contact within the U. S. Army Corps of Engineers and dredging industry.
- d. Contacts with professional dredging associations.
- e. Considerations for system interfacing and operating requirements.
- f. Procurement and distribution pathways for dredging instrumentation.
- g. Examination of potential OEM approach for instrumentation vendors.

Stage 13

Tests were continued on the 1.2-m- (4-ft-) diameter by 1.8-m- (6-ft-) long 15.9-mm (0.63-in.) wall spool piece for proper operation. Although the signal strength received on the 0.8-rad (45-deg) diametrical path was strong, it was at a "wrong" frequency of about 100 kHz instead of the calculated 80 kHz. This meant that the beam path was "too steep" for the as-built angle between the arrays, which in turn meant that there was a signal propagating in the pipe wall. This was proven by physically blocking the desired between-arrays path with closed cell foam without causing signal interruption. It turned out that the reason the signals were as strong as they were was that the pipe wall was at resonance in the thickness mode (one-half wave) at 100 kHz. The system was not intended to depend on wall resonances for operation, because each pipe will have different resonant characteristics.

A computer simulation program was developed to help visualize the beam forming and acoustic propagation of the different array configurations, pipe wall thickness, and frequency. While the program did not model resonant effects in the pipe wall, it was useful for visualizing what is going on in the pipe.

The propagating signal was also measured directly using a small omnidirectional hydrophone suspended in water along the acoustic path. This enabled confirmation of the actual propagation of signals in water. It was verified that the signal propagated on the diametrical paths in both the 9.5- and 15.9-mm- (0.38- and 0.63-in.-) thick pipes.

The axial propagation of signals in the pipe wall for part of the acoustic path may explain the reason for the low reading on the diametrical path during the Colton tests in the fall of 1994. At that time it was observed that the velocity measured on the central diametrical path was about 6 percent lower than that measured by a standard flow meter upstream and also was lower than the velocities observed on the adjacent chordal paths. This was not expected to occur under the near-ideal conditions of the Colton test; the maximum velocity should have been at the pipe center line.

Turning to the 0.5-rad (30-deg) chordal path location, propagation between the arrays was achieved by moving the arrays away from each other on the pipe wall. However, it was becoming apparent that tests were being conducted at frequencies too high for this wall thickness pipe. The prototype electronics were modified to handle lower frequencies, down to 40 kHz. It was possible to repeat the tests using the same arrays by reconnecting them in parallel-series to effectively increase the spatial wavelength by a factor of two.

Wheeler Field Test

After successfully testing the flow meter at the ORE facility, Alden Research Laboratory, and on a dam penstock, the next phase consisted of testing the flow meter on a dredge pipe carrying suspended sediment.

ORE gave the following requirements for the field test:

“We would like to perform a test on a working dredge. We need a suitable location on the dredge, ideally with a 30 to 48 inch steel or plastic pipe. This test can be accomplished with a relatively short lead time, since all materials required are in hand. We would prefer a plastic pipe if possible, since this would give us the best possible signal strength based on our current understanding of the operation of these transducers. Ideally we would want to conduct preliminary tests in the facility at ORE on a similar size / material pipe section before the test.”

It was pointed out to ORE that the pipes of every large dredge are made of steel in order to withstand the abrasive action of sand flowing at a high velocity. Plastic pipes are used on some small portable dredgers, with operations on a very small scale of time, cost, and quantities of sediment removed. Hence they are not anxious to install any expensive, elaborate, and accurate devices for measurement of flow through the pipe. Hence, the field test had to be conducted on a steel pipe. Regarding the size of pipe, it was pointed out that most of even the large dredgers have pipe diameters in the range of 0.6 to 0.9 m (24 to 36 in.). Hence it is difficult to find working dredgers with large-diameter pipes.

It was possible to obtain permission and cooperation of the U. S. Army Engineer District, New Orleans, for conducting a field test on a large dredger, *Wheeler*, operated by the District. Details of the pipe were communicated to ORE, and a steel spool piece of the same kind was procured by ORE. Adequate preliminary laboratory tests were conducted at the ORE facilities to make sure that the actual field tests could be conducted successfully.

The field tests were performed on the dredger *Wheeler* during the week of 3 June 1996. Because of a very limited access to the horizontal and vertical pipes on the dredger, the flow meter was installed on an 0.8-m-(31.5-in.) diameter horizontal pipe flowing aft on the starboard side of the dredger. Two transducers were installed on the pipe (Figure 25). The main difficulty experienced while pasting the transducers was the high temperature during the hot summer days in June. The pipe exposed to direct sunlight was very hot and the properties of the fast-setting epoxy changed due to the high temperature. The difficulty was overcome by using a different formulation of epoxy. One of the two arrays was made with several extra elements so that different path angles could be tested. Electrical cable had to be longer than expected due to the remote location

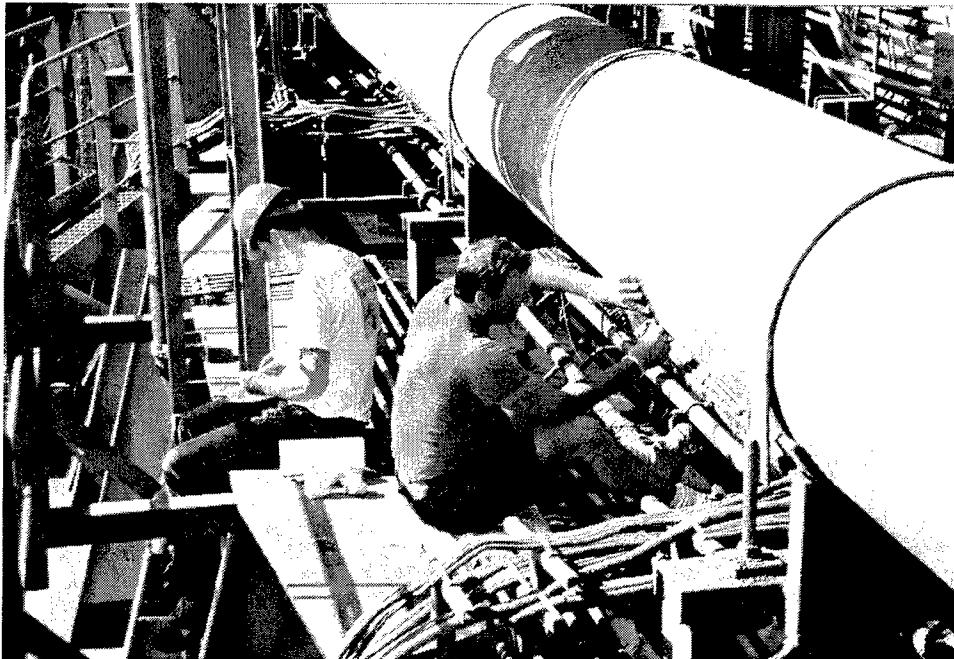


Figure 25. Transducer being installed on dredge pipe of *Wheeler*

of transducers from the outlets on the dredger. Hence the cables were required to be spliced.

Two different systems (Figure 26) were carried on the dredger: the PC system and the prototype production system. The PC system permitted viewing of the wave forms and was more flexible for conducting different tests easily. On the other hand, the prototype system contained more software. By using extra elements of one transducer, several experiments were conducted to determine the optimum configuration of the acoustic arrays and the electronics. Final tests were conducted in the presence of the captain of the ship, who wanted to witness the results by varying the flow velocity and sediment contents through the pipe. All the tests were performed satisfactorily. An example of the test record is given in Figure 27.

The following conclusions were drawn from the tests:

- a. Both the systems measure flow when there is water in the pipeline. The measured flow rates agreed fairly well with the onboard instrumentation.
- b. The system software had difficulty with the highly variable signal strength caused by occasionally entrained air in the pipe. This problem can be overcome by modifying the software to accept only positive velocities, since in dredging applications the flow is only in one direction. More sophisticated filtering algorithms can be used to ensure that unrealistic flow rates are not included in the output.



Figure 26. Data acquisition system used on *Wheeler*

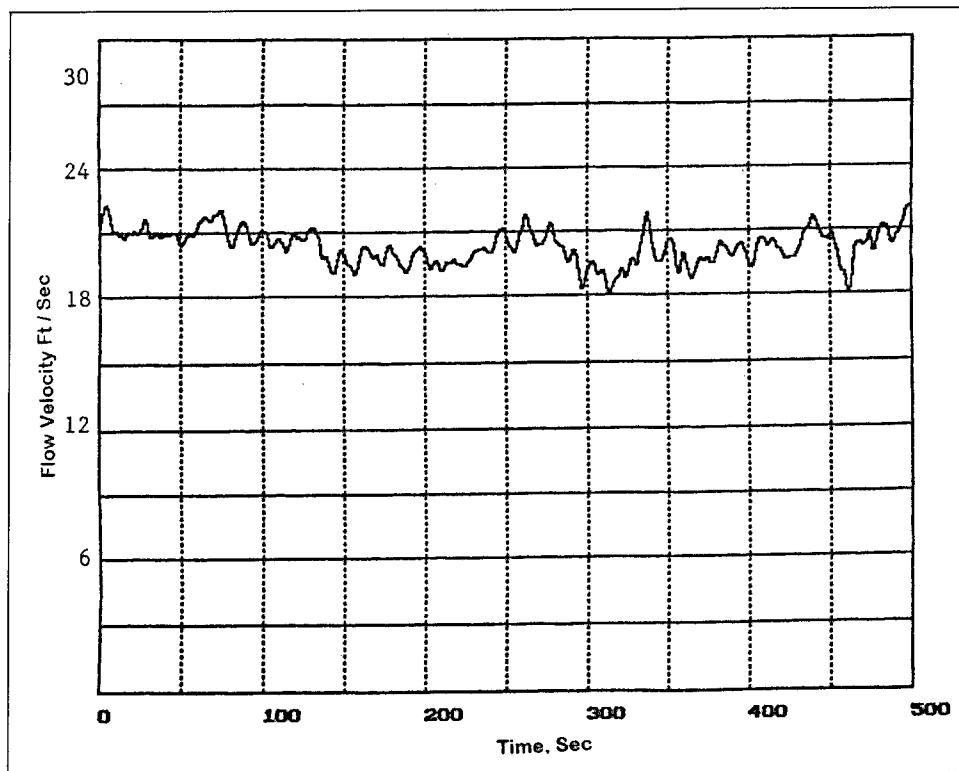


Figure 27. An example of test record obtained on dredge pipe (to convert flow velocities from ft/sec to m/sec multiply by 0.3048)

- c. A permanent installation should be done at a location on the pipeline that will always be full of water.
- d. A low concentration of suspended sediment in the dredge pipe (slurry density on the order of 1.1) did not appear to attenuate the acoustic signals excessively. At times the signals were lost, but this appeared to be caused by the entrained air in the system. Signal attenuation would also depend on the sediment characteristics.

Stage 14

After extensive tests with diametrical paths on the 1.2-m-(4-ft-) diameter 15.9-mm- (0.63-in.-) thick pipe, it was possible to achieve satisfactory signal levels. Experiments were conducted with lower frequency and wider spacing of elements; however, they were not successful in lowering the operational frequency to the desired level. In spite of this limitation, enough data were obtained to be able to construct a diametrical array for a satisfactory performance.

A search for market opportunities to demonstrate the feasibility of the externally mounted array concept was continued. Difficulties were experienced with pipelines having 15.9-mm- (0.63-in.-) wall thickness; however, extensive testing of the system provided confidence in satisfactory operation of the flow meter with a 9.5-mm-(0.38-in.-) thick and thinner pipe wall.

Stage 15

The final report on the development of the externally mounted transducer type acoustic flow meter was prepared. Marketing efforts were continued. Improvements were made in the production unit. Final detailed drawings and parts lists were prepared. These are too voluminous to be included in this report. The joint CPAR-CRDA between ORE and WES ended in September 1996.

Software for Data Processing

The flow meter software is controlled through a handheld display / keypad that allows the operator full access and control of all operational parameters as well as the display of all output variables. Flow meter output is also available over an RS-232 format.

In order for a travel time flow meter to operate properly it is necessary to input the "as-built" path lengths, angles, pipe diameter, and several other parameters. Once entered, these parameters are stored in nonvolatile memory until changed by the operator. A flowchart of operations is given in Figure 28. During operation, the flow meter electronics generates high-voltage (500-v) pulses at approximately 100 kHz frequency into each transducer array in sequence. The frequency is optimized for each path location. The received signals from the opposite transducer are processed to determine the signal strength for Automatic Gain Control and to determine the exact time of arrival of the pulse. This detection method is key to the operation of the flow meter. The system must determine the correct receive cycle and the zero-crossing times of several of the cycles in the received signal in order to achieve the less than 10 nanosecond differential timing accuracy required for accurate velocity measurement on each path. In order to improve the signal strength, up to 16 successive receive signals can be "stacked" together in real time. This improves operation in high attenuation environments, such as expected and encountered on the tests conducted on the Dredge Wheeler. The velocities and flows are then filtered to remove any obviously "bad" (impossible) readings, and the resulting flows are averaged. A printout of the software developed for this purpose runs into about 100 pages and has not been included as a part of this report. A tank simulation program has been written to estimate the sound pressure on the walls of a pipe. A printout of this program runs into 20 pages and has not been included in this report because its main purpose was to assist during the research and development stage of the project. In order to illustrate the usefulness of this tool, results of frequency response of tank and simulation are given in Appendix E.

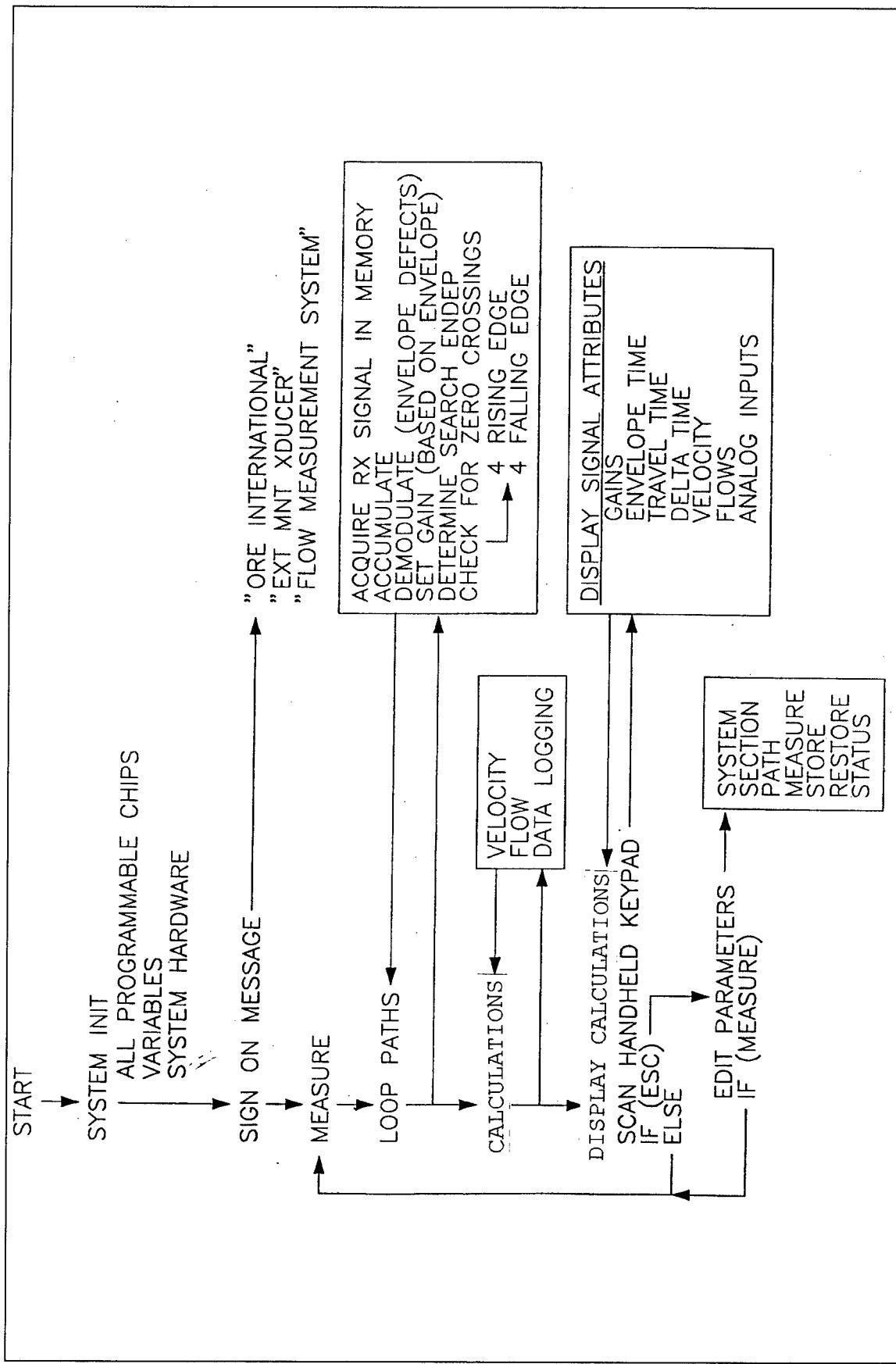


Figure 28.

Flowchart of Accusonic flow meter operation

5 Conclusions and Recommendations

General Conclusions

Project objective

The project objective was to develop an acoustic flow meter combining the high absolute accuracy of multipath measurement with the economy and simplified installation of less accurate clamp-on flow meters for application in water supply and slurry transport industries. This objective has been achieved.

The product

The product developed as a result of this research is a one-to three-path acoustic flow meter transceiver, with transducers consisting of phased arrays mounted conformally to the outside of the pipe. The transducers are constructed from a relatively new piezoelectric material called PVDF. This material was found to be ideal for a flexible production transducer easily installable in the field on different size pipes. The system uses digital signal processing technology. The clamp-on feasibility is an important feature of the new meter. Measurement accuracy is estimated to be up to ± 1.0 percent of the flow. The transducers are driven by a modified Acusonic flow meter using digital signal processing (DSP) technology, which consists of the following:

- a. Conformal phased array transducers applied to a prepared surface at four to eight locations on the exterior of the pipeline. In the case of a suction dredge, this could be either on the dredge itself or at another convenient location along the pipeline.
- b. A signal processing unit that performs the following:
 - (1) Generates coded acoustic signals for transmission between pairs of transducers installed above.

- (2) Generates coded acoustic signals for transmission between pairs of transducers installed above.
- (3) Receives and time-compresses the signals.
- (4) Determines precise acoustic travel times between one or more transducer pairs.
- (5) Employs these measured travel times to determine the flow rate using acoustic flow rate measurement algorithms well known to the flow measurement industry.

Advantages

The advantages of the clamp-on type flow meter are that it requires no contact with the fluid, no welding or cutting of pipe, and no operational shutdown for installation or maintenance. In addition the installation is quick, easy, and low cost.

Technology

The technology consists of the following:

- a. Conformal phased array transducers applied to a prepared surface at four to six locations on the exterior of the pipeline.
- b. A signal processing unit which
 - (1) Generates acoustic signals for transmission between pairs of transducers installed above.
 - (2) Receives and time-compresses the signals.
 - (3) Determines precise acoustic travel times between one or more transducer pairs.
 - (4) Employs these measured travel times to determine the flow rate using acoustic flow rate measurement algorithms well known to the flow measurement industry.

Principle

The new meter is a differential travel-time acoustic meter. The system measures the difference in travel time between signals propagating upstream and downstream between multiple pairs of transducers. Under no flow conditions will the travel time in each direction be the same. Under fluid flow conditions, the travel time in the downstream direction will be

less than that in the upstream direction. The difference in travel time is correlated to the flow velocity.

Calibration

A velocity formula is used to correct the velocity readings resulting from variations in the speed of sound in the fluid. When the path lengths and angles are accurately known, it is not necessary to "wet" calibrate the meter. It is sufficient to enter the as-built path dimensions along with the pipe diameter in order to have a "dry-calibrated" volumetric flow meter. This is an extremely important feature of this meter as it is very difficult to calibrate flow meters in larger pipe sizes.

Testing and verification

The new flow meter was tested extensively at the following four locations during the development stages. These tests have provided confidence in the satisfactory performance of the flow meter.

- a. At the facilities specially created at ORE Laboratory.
- b. At the Alden Research Laboratory using the weighing tank facility for verification.
- c. On the penstock of the hydroelectric project in Colton, NY. An already installed four-path flow meter was used for verification of measurements.
- d. On the pipeline of the dredger *Wheeler*.

Marketing

Marketing efforts have been and will be focused on promotion of the flow meter to the dredging industry. The new capabilities of the DSF will be promoted to the industry, highlighting its potential for enhancing production during field dredging operations. In addition, the product should have many applications in acoustically "cleaner" water, such as the hydroelectric, wastewater, and potable water industries, where economy and ease of installation are often important considerations.

Competitive advantages

Relative to the existing slurry flow meters (e.g., clamp-on Doppler meters and magnetic flow meters), the new meter has the following advantages:

- a. High accuracy.
- b. Straightforward installation.
- c. Simple operation.
- d. Reliable performance.
- e. Low maintenance.
- f. Long service life.

Cost

The present price of a flanged 0.76-m (30-in.) rubber-lined magnetic flow meter is about \$25,000 not including installation and downtime. A somewhat lower cost is anticipated for the new externally mounted transducer type acoustic flow meter without the downtime penalty required for installation. The cost of an acoustic flow meter is relatively independent of size, unlike competitive technologies where the cost rises at a linear or faster rate with the size of meter. Therefore, the acoustic meter will always be cost competitive with other methods in the larger sizes. Another advantage of acoustic flow meters, with externally mounted transducers, is that in the event of a transducer or other failure the system can be repaired without interruption of the flow. This is a significant advantage that helps justify any additional cost of the acoustic flow meter over competing technology, thus lowering the size threshold where it becomes competitive.

Service life

Service life of the meter should be unlimited, because there should be no wearing out of the equipment, with no flow meter parts in direct contact with the slurry flow being measured.

Limitations

At the present stage of development, the meter can be used under the following limitations:

- a. Pipe diameter needs to be larger than 0.6 m (24 in.).
- b. Pipe wall, if made of steel, should be thinner than 15.9 mm (0.63 in.).
- c. Slurry density should not exceed 1.1.

Potential Impact on U.S. Industry

Any situation where large volumes of water or slurry are being moved through pipelines should be a potential application of this technology. An accurate flow rate measurement will allow optimum equipment operation by showing the operator the best operating point on his system for maximum removal or transport of material, as well as for detection of system performance degradation.

This should include the mining and dredging industries, as well as others, possibly including coal slurry pipelines. Of course, this approach has many potential advantages in the wastewater and water resource industries as well, not to mention clean (municipal) water applications requiring easy to install accurate flow meters.

An additional possible application for any of these examples would be leak detection, where the difference in measured flow rates at both ends of the pipeline would be used to detect leakage in or out of the pipeline.

Potential Impact on the Corps of Engineers

Dredging

Direct benefits include the accurate determination of dredged material removal by combining the proposed flow meter with a density gauge. The system could easily be built to accommodate the density subsystem output, so that mass flow rate of dredged material is also a system output, forming an integrated production meter. This would benefit the Corps by more accurately measuring contractor performance for payment as well as for comparison with expected dredge performance.

Indirect benefits would include an improved basis for design of dredging equipment. Field performance could be accurately determined at lower cost than with existing technologies, and the rate of equipment degradation could be more accurately determined, particularly related to dredging of different materials.

Hydroelectric projects

Accusonic has been a market leader for the supply and installation of high-accuracy acoustic flow meters to the hydroelectric industry and the Corps of Engineers for many years. However, one of the limitations has always been the lack of a multiple-path chordal clamp-on flow meter design. Any location where the pipeline is large and the pressure low is a potential candidate for this type of flow meter.

Recommendations

The following recommendations are made:

- a. The product developed as a result of this research is a one- to three-path acoustic flow meter transceiver, with transducers consisting of phased arrays mounted conformally to the outside of a pipe. This clamp-on type acoustic flow meter is recommended for use by the private industry and by the Corps of Engineers for flow measurement in a low-pressure, 0.6-m- (24-in.-) or larger diameter steel pipe with a wall thickness less than 15.9 mm (0.63 in.), carrying sediment-free or near-sediment-free water. Examples of such use are sewer pipes and dam penstocks.
- b. The flow meter may also be tried on similar pipes on a dredge when the slurry density is less than 1.1.

Further Information

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6 Marketing and Technology Transfer

Marketing Plans and Related Activities

The prototype flow meter developed under this CPAR Project will serve as the basis for finalizing a standardized design and production-ready configuration for a full-function dredge slurry flow meter (DSF), comprising an integrated electronics console with analog / digital outputs, operator interface, externally mounted conformal pipe wall transducers and cabling.

Initial marketing efforts have been focused on promotion of the flow meter to the dredging industry. The new capabilities of the DSF for high-accuracy slurry flow monitoring will be promoted to the industry, highlighting its potential for enhancing production during field dredging operations. Competitive advantages of the DSF relative to existing slurry flow meters (e.g., clamp-on Doppler meters and magnetic flow meters) will be emphasized and will include the following features:

- a.* High accuracy.
- b.* Straightforward installation.
- c.* Simple operation.
- d.* Reliable performance.
- e.* Low maintenance.
- f.* Long service life.

The functional design for the production DSF will include easy interfacing (via analog current or voltage output proportional to flow rate) with dredge Production Meter Systems (PMS) used to indicate slurry flow rate, slurry density, and dredged material production (cubic yards/hour). Data averaging of individual flow rate measurements (taken at about one-second intervals) over user-selectable durations will be made available in order to

stabilize indicated flow readings and provide better feedback to dredge operators for judging the effects of cutterhead depth and pump speed settings. Programmable alarm condition settings for alerting operators to low-flow conditions will also be available.

DSF sales and distribution activities will be planned and coordinated under the direction of the Accusonic marketing department, including utilization of Accusonic's six existing regional U.S. sales/service offices (California, Massachusetts, South Carolina, Texas, Washington, and Wisconsin). As with the other Accusonic flow meters, units destined for customers within the domestic U.S. territories will be handled as factory-direct sales. This is consonant with the potential dredging market for DSF sales, comprising a finite and well-integrated customer set, relatively limited in size, organization, number of operating companies, and their geographic distribution. In this respect the market segmentation characteristic of the dredging industry (operators and major equipment suppliers) is somewhat similar to Accusonic's hydroelectric flow meter market, allowing an effective focus for sales and promotional activities to be readily developed.

International DSF sales and product export distribution will be accomplished through a network of foreign regional sales representatives. It is anticipated that several of the existing sales representation companies involved with ORE's marine- and offshore-related product lines will be included in the international DSF sales and service network. Accusonic has had extensive experience in establishing effective international sales and service networks, typically incorporating exclusive sales representation organized by customer sets and geographical territories. In some cases, joint venture arrangements have been successfully implemented and developed for this purpose.

In addition, opportunities for original equipment manufacturer (OEM) sales will be explored and pursued with both domestic and international dredging instrumentation system and equipment suppliers. As soon as practicable, Accusonic will also include the DSF and related components on its existing General Services Administration schedule for supply of DSF units to the U.S. Army Corps of Engineers.

DSF promotional activities will be conducted to ensure awareness of DSF capabilities and availability to the relevant dredging industry market. In general, the primary market segment is defined by dredging operations using slurry pipes greater than 0.6-m- (2-ft-) diameter with pipe wall less than 9.5 mm (0.38 in.) thick.

In addition to direct sales contacts to be made with relevant dredging companies, the following promotional activities will be conducted to increase industry awareness and ensure penetration into the operational dredging market:

- a. Advertising in major dredging periodicals.

- b. Listings in dredging supplier directories.
 - c. Product news releases for journals and newsletters.
 - d. Preparation of brochures/informational materials.
 - e. Exhibiting at trade shows and dredging conferences.
 - f. Presentation/publishing of technical and applications papers.
 - g. Direct mail campaign.
- h. Awareness among Army Corps of Engineers District Offices and key personnel.

A preliminary "Fact Sheet" for distribution to U.S. Army Corps of Engineers offices and key personnel has been prepared (Appendix F). Descriptive data sheets on the DSF will be prepared for use at dredging industry trade shows and in promotional mail-outs.

Cost

The cost of these systems should be very competitive with existing technology. For example, the present price of a flanged 0.76-m (30-in.) rubber-lined magnetic flow meter is about \$25,000 not including installation and downtime. A somewhat lower cost is anticipated for the new externally mounted transducer type acoustic flow meter without the downtime penalty required for installation. The extensive use of microelectronics and low cost of installing field transducers on the exterior of existing piping will keep costs low in the future. A Doppler meter used in this application, although much less expensive, is much more error prone due to the changing backscatter characteristics of the slurry as its density changes during operation, causing the depth of penetration of the sonar signal to fluctuate, which results in different portions of the boundary layer to be measured.

A characteristic of all acoustic flow meters is that their cost is relatively independent of size, unlike competitive technologies including differential producers (venturis), and magnetic flow meters where the cost rises at a linear or faster rate with the size of meter. Therefore the acoustic meter will always be cost competitive with other methods in the larger sizes. This is true regardless of the manufacturer.

Another advantage of acoustic flow meters with externally mounted transducers is that in the event of a transducer or other failure, the system can be repaired without interruption of the flow. This is not the case with magnetic or venturi type meters, where the pipe must be taken out of service to replace the meter section. This is a significant advantage that helps

justify any additional cost of the acoustic flow meter over competing technology, thus lowering the size threshold where it becomes competitive.

Electronics in general and microprocessors in particular continue to experience a downward cost trend. The flow meters that ORE sells now cost less than one tenth of what they cost 15 years ago, and they are also a superior and more reliable design, with much greater capabilities. It is safe to assume that this trend will continue, so that even if the production cost is high initially, it will drop with time. This is definitely not the case with flow rate measurement systems such as the magnetic or venturi type meters. Their cost is rising because of the rising cost of the physical spool piece, which is a part of each meter installation.

Furthermore, there is a potentially large market for the new technology for measurement of relatively clean water and other fluids. Therefore the economies of scale dictate that this product will have to be made relatively inexpensive to successfully penetrate these other markets, some of which are dominated by the present products of ORE.

Technology Transfer

There are two areas where the technology developed for this project is either currently being transferred or will be transferred in the future. The most immediate transfer is the use of the digital signal processor (DSP) based transceiver components and some of the software for the present short-pulse flow meter product lines. Improvements have been made possible in the processing of the signal-to-noise ratio by "stacking" several signals together. Hence operation in higher attenuating fluids, most notably wastewater, is improved significantly. This is becoming a larger part of Accusonic's business as a result of new Federal requirements for water quality in the Nation's rivers, estuaries, and waterways.

In addition, the DSP module has been incorporated into a completely different product designed to measure the rate of cavitation erosion in hydro pumps and turbines by processing the noise signals picked up by an accelerometer mounted on a wicket gate arm. The DSP performs real-time fast Fourier transform (FFT) analysis of the noise, which is modulated by the passage of the turbine blades past the wicket gate.

Another potential area is in a wider use of PVDF materials in the internally mounted transducers used both for velocity and level measurements in open channels. These channels are generally located below the ground level and are made of reinforced concrete. They are not suitable for external mounting. Again, the largest market for this application is in wastewater, where it is very important to build transducers that do not protrude into the fluid, because of the potential problem caused by the accumulation of rags and other debris on the transducer.

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Appendix A: Mathematical Relationships for Travel of Acoustic Signal and Technical Details of New Flow Meter

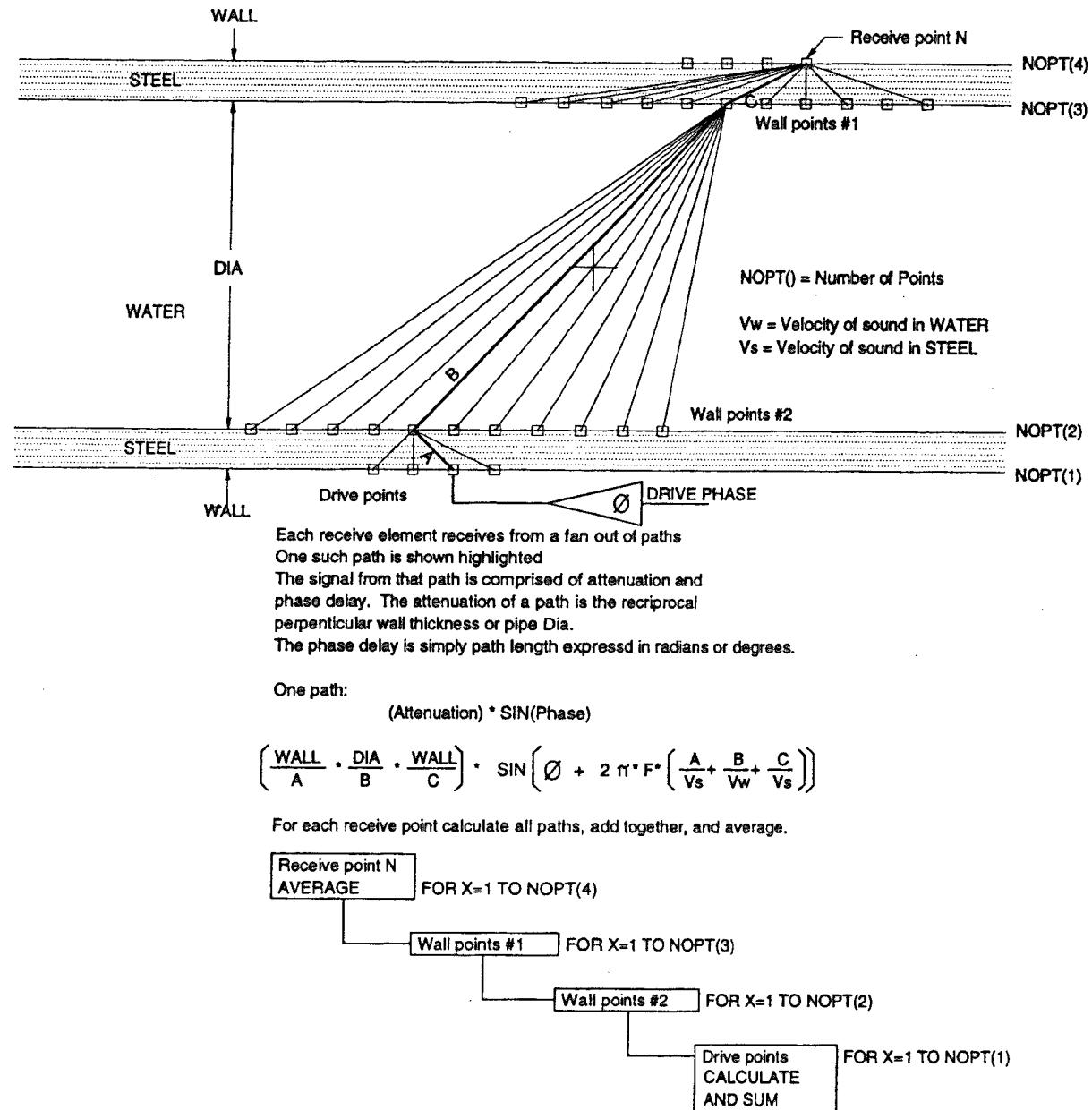


Figure A1. Computer model for array response simulation

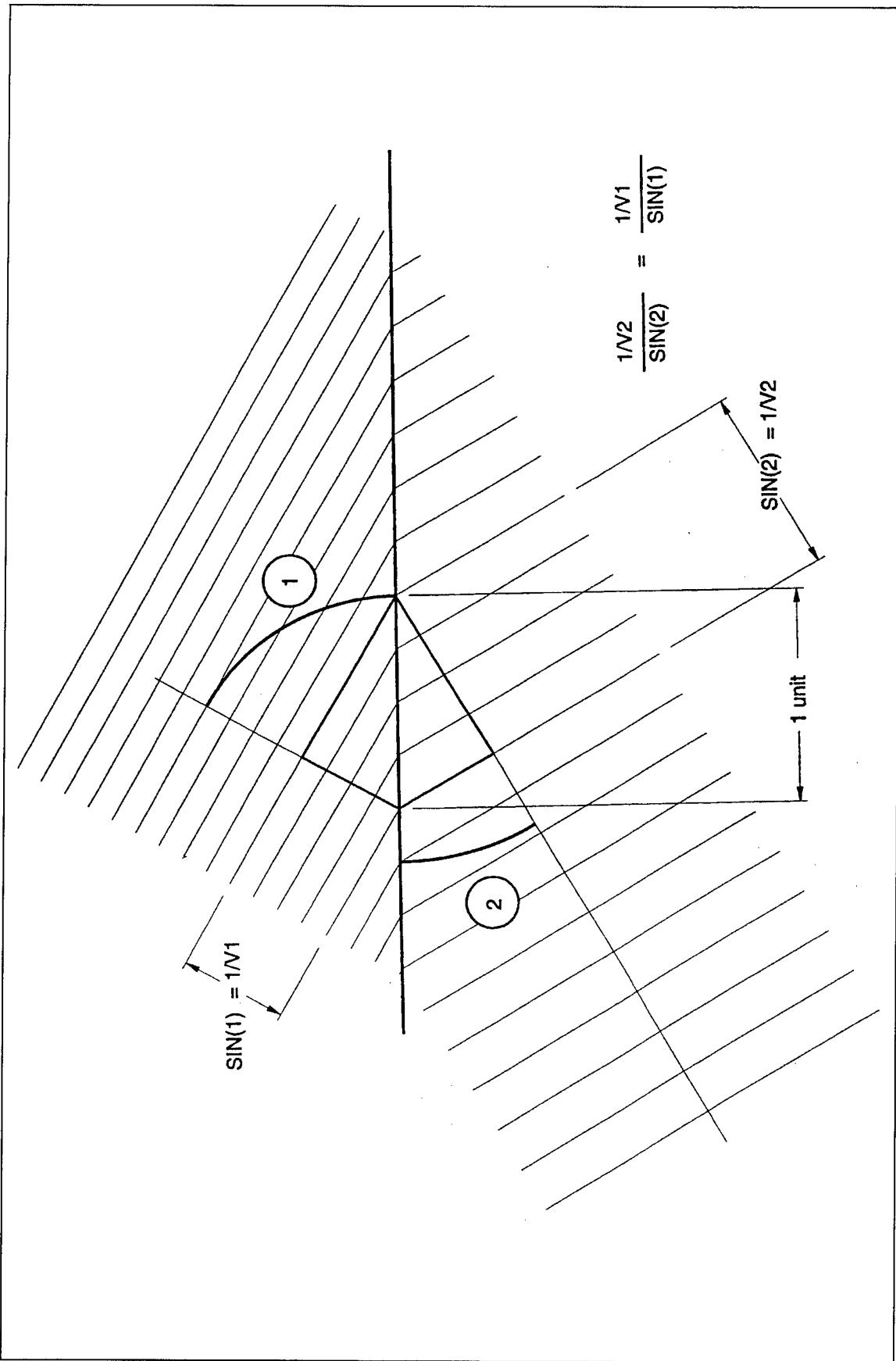


Figure A2. Acoustic wave propagation across steel/water interface

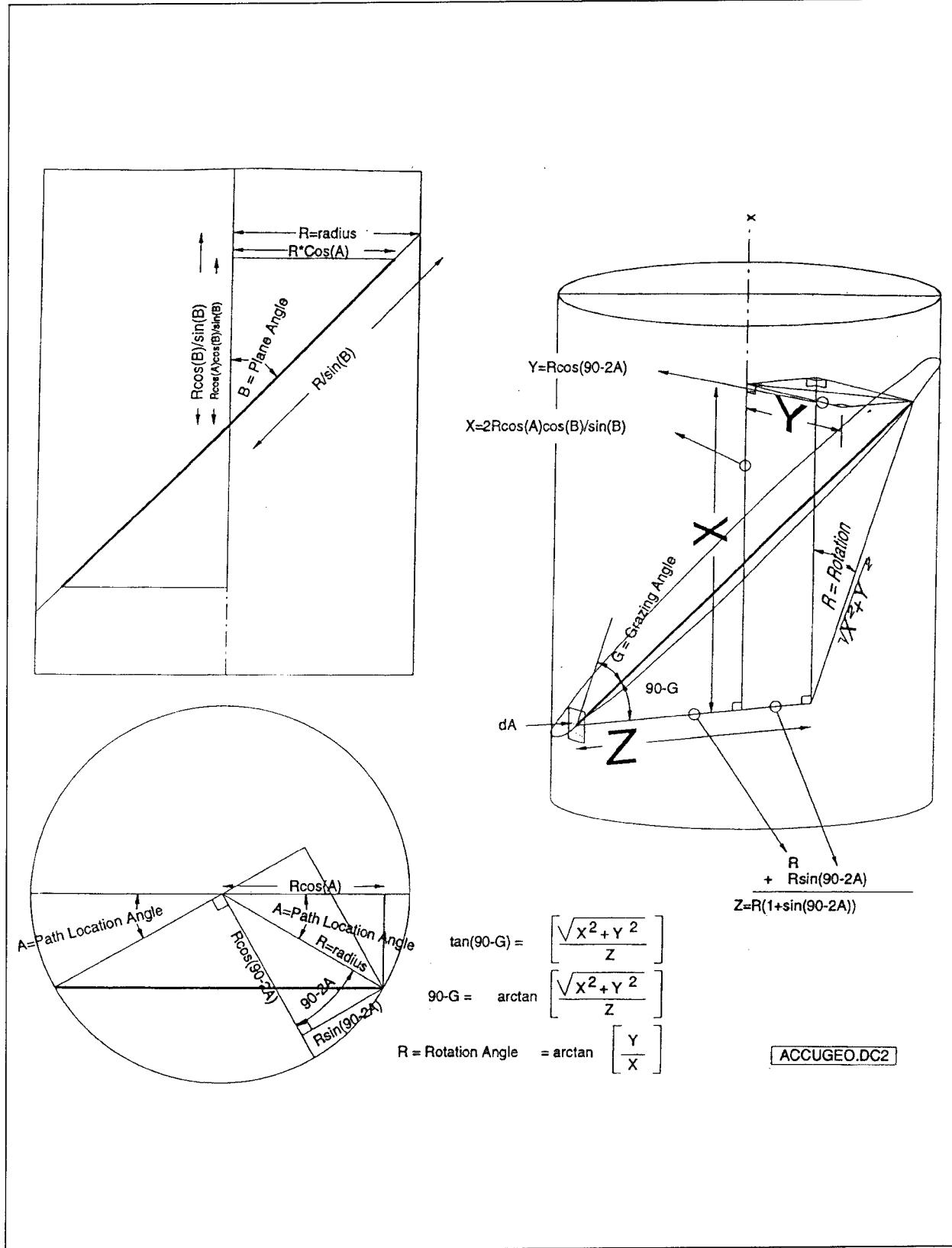


Figure A3. Grazing angle geometry for chordal path

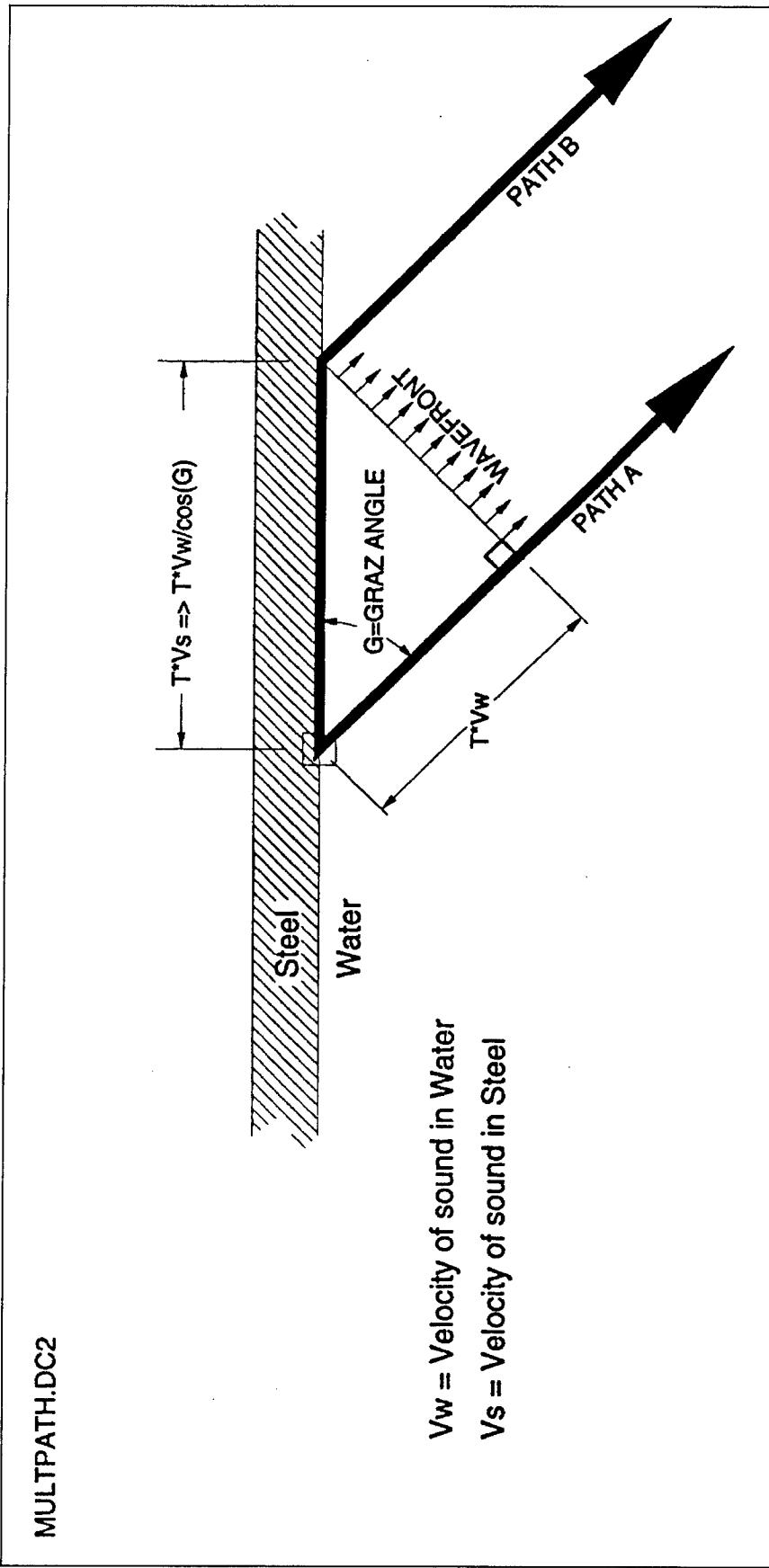


Figure A4. Grazing angle as determined by ratio of steel and water sound velocities

At what point "X" does travel time
of the direct path equal the alternate path?

MULTPATH.DC2

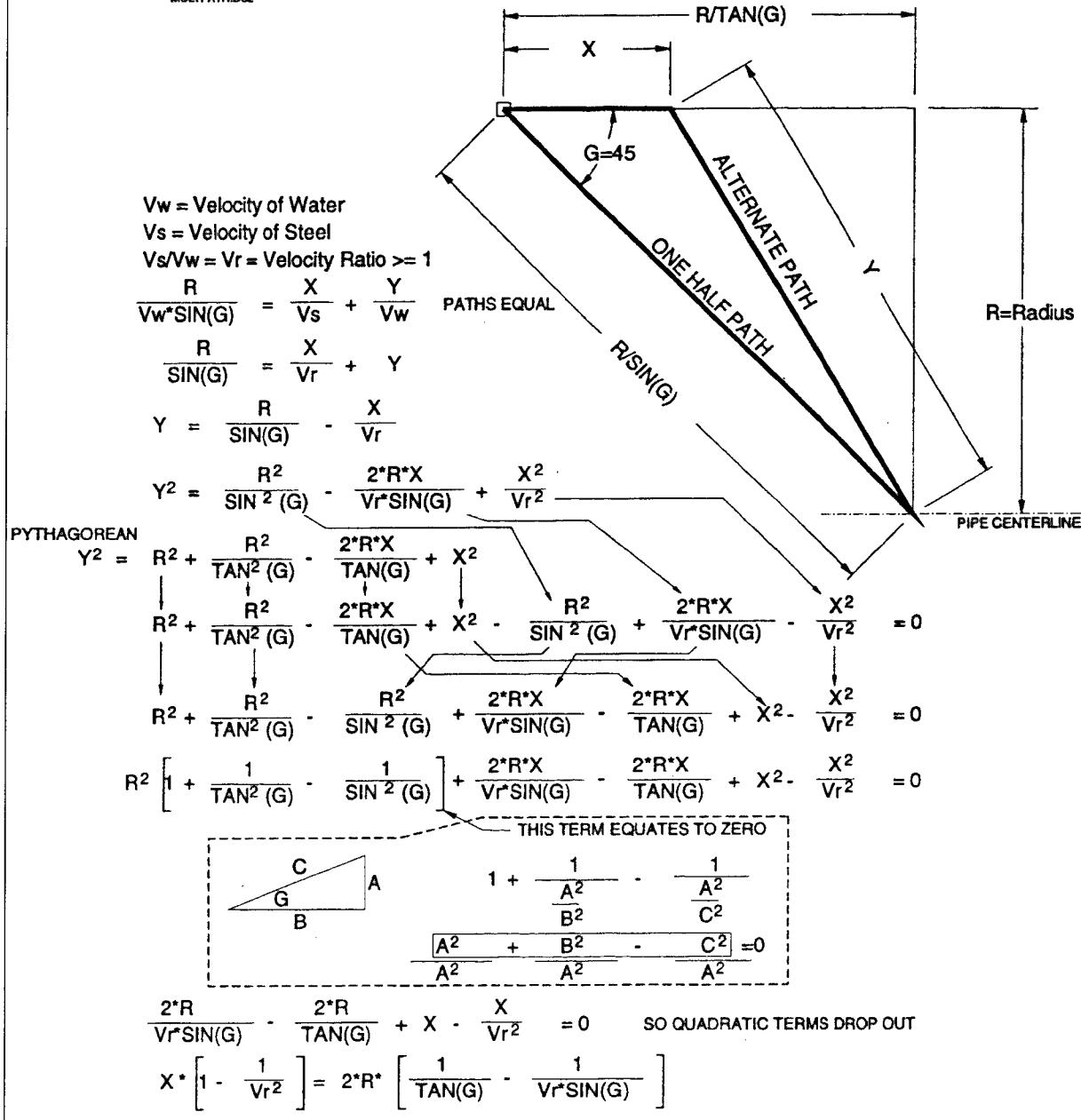


Figure A5. Diametrical path geometries showing conditions for two simultaneous paths

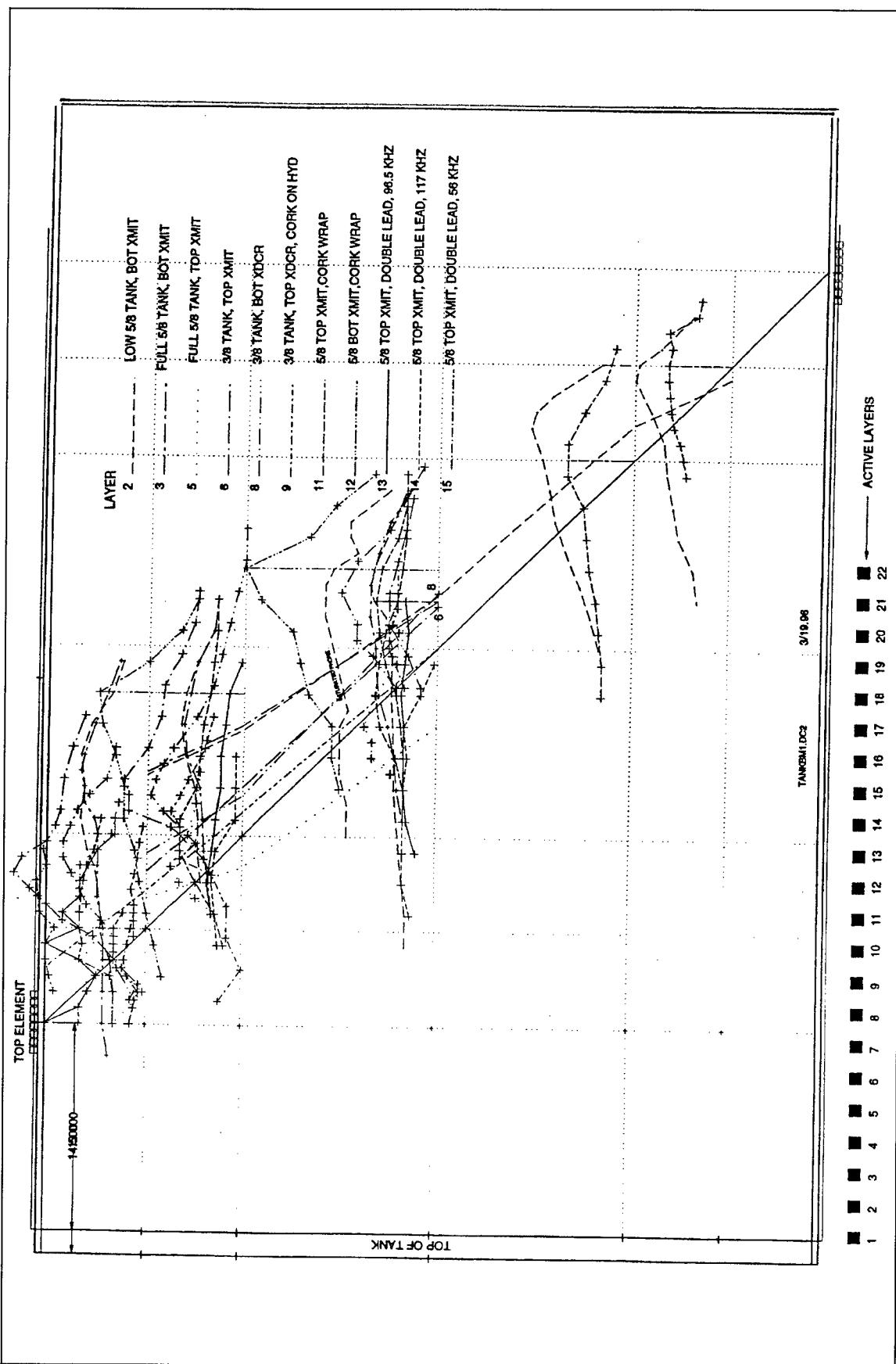


Figure A6. Measured signal strengths along acoustic path in test tank

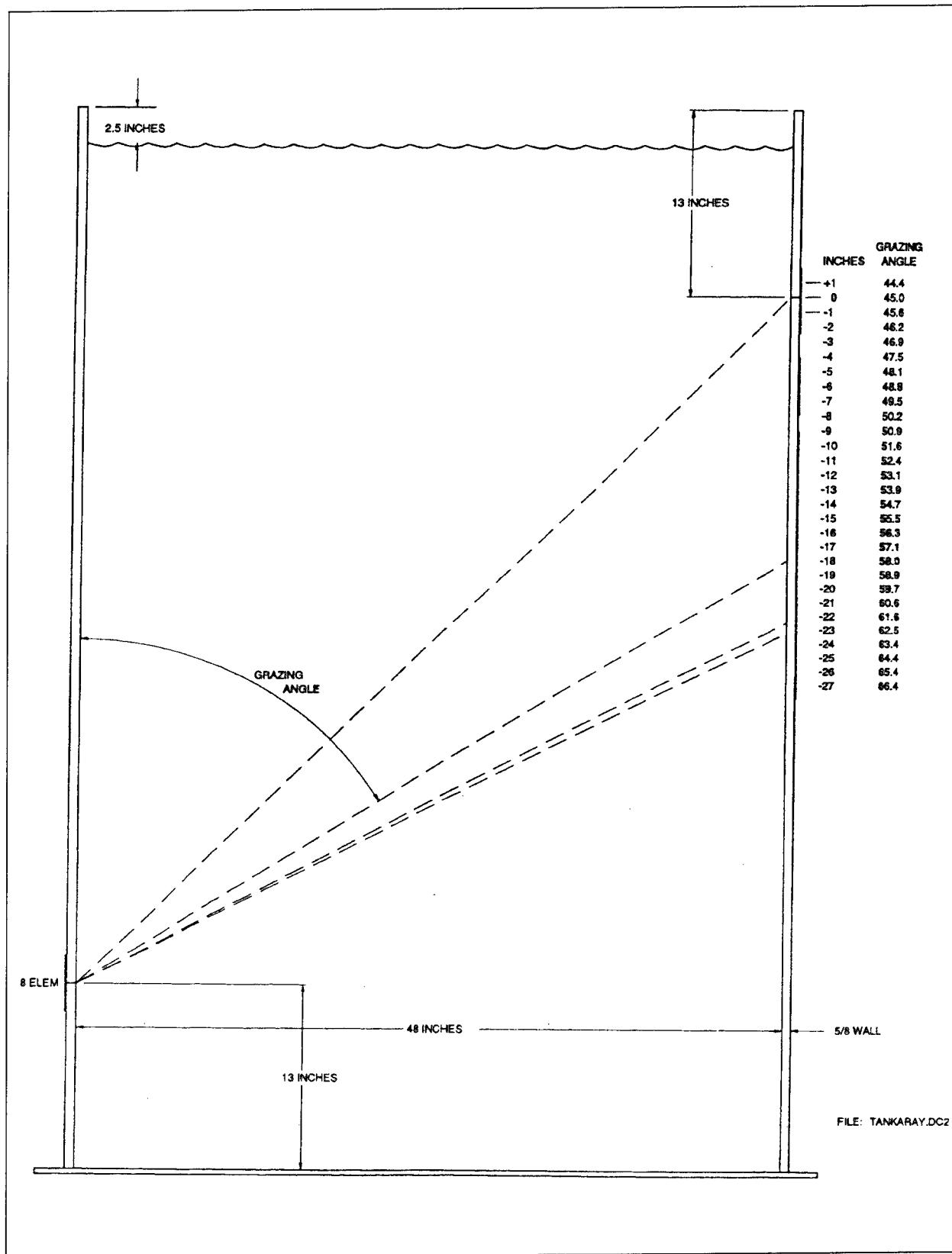


Figure A7. Grazing angle versus path positions for diametrical path

Transducer Placement (Grazing Angles, Rotation Angles and Locations)										String Dimensions				
Pipe Radius	Path Location Angle			Plane Angle			Grazing Angle			Rotation Angle		String Dimensions		
	Deg	Radians	Deg	Deg	Radians	Deg	Sqr(X^2+Y^2)	Deg	Radians	Deg	Radians	Circum	Height	Diagonal
24	70	1.222	45	0.785	16.42	15.48	5.61	22.53	14.00	0.244	43.22	0.754	16.42	23.46
24	65	1.134	45	0.785	20.29	18.39	8.57	27.38	17.39	0.303	42.19	0.736	20.94	29.16
24	60	1.047	45	0.785	24.00	20.78	12.00	31.75	20.70	0.361	40.89	0.714	25.13	34.75
24	55	0.960	45	0.785	27.53	22.55	15.79	35.59	23.93	0.418	39.32	0.686	29.32	40.22
24	50	0.873	45	0.785	30.85	23.64	19.83	38.87	27.03	0.472	37.45	0.654	33.51	30.85
24	45	0.785	45	0.785	33.94	24.00	24.00	41.57	30.00	0.524	35.26	0.615	37.70	33.94
24	40	0.698	45	0.785	36.77	23.64	28.17	43.71	32.80	0.572	32.73	0.571	41.89	36.77
24	35	0.611	45	0.785	39.32	22.55	32.21	45.33	35.40	0.618	29.84	0.521	46.08	39.32
24	30	0.524	45	0.785	41.57	20.78	36.00	46.48	37.76	0.659	28.17	0.464	50.27	41.57
24	25	0.436	45	0.785	43.50	18.39	39.43	47.23	39.86	0.696	22.91	0.400	54.45	43.50
24	20	0.349	45	0.785	45.11	15.43	42.39	47.67	41.64	0.727	18.98	0.330	58.64	45.11
24	15	0.262	45	0.785	46.36	12.00	44.78	47.89	43.08	0.752	14.51	0.253	62.83	46.36
24	10	0.175	45	0.785	47.27	8.21	46.55	47.98	44.14	0.770	9.85	0.172	67.02	47.27
24	5	0.087	45	0.785	47.82	4.17	47.64	48.00	44.78	0.782	4.98	0.087	71.21	47.82
24	0	0	45	0.785	48.00	0.00	48.00	48.00	45.00	0.785	0.00	0.00	75.46	48.00

RD-296

S= Dwg ACCUGEO.DC2 for illustration

12/29/05 ABG

Figure A8. Grazing angles, rotation angles and locations for transducer placement

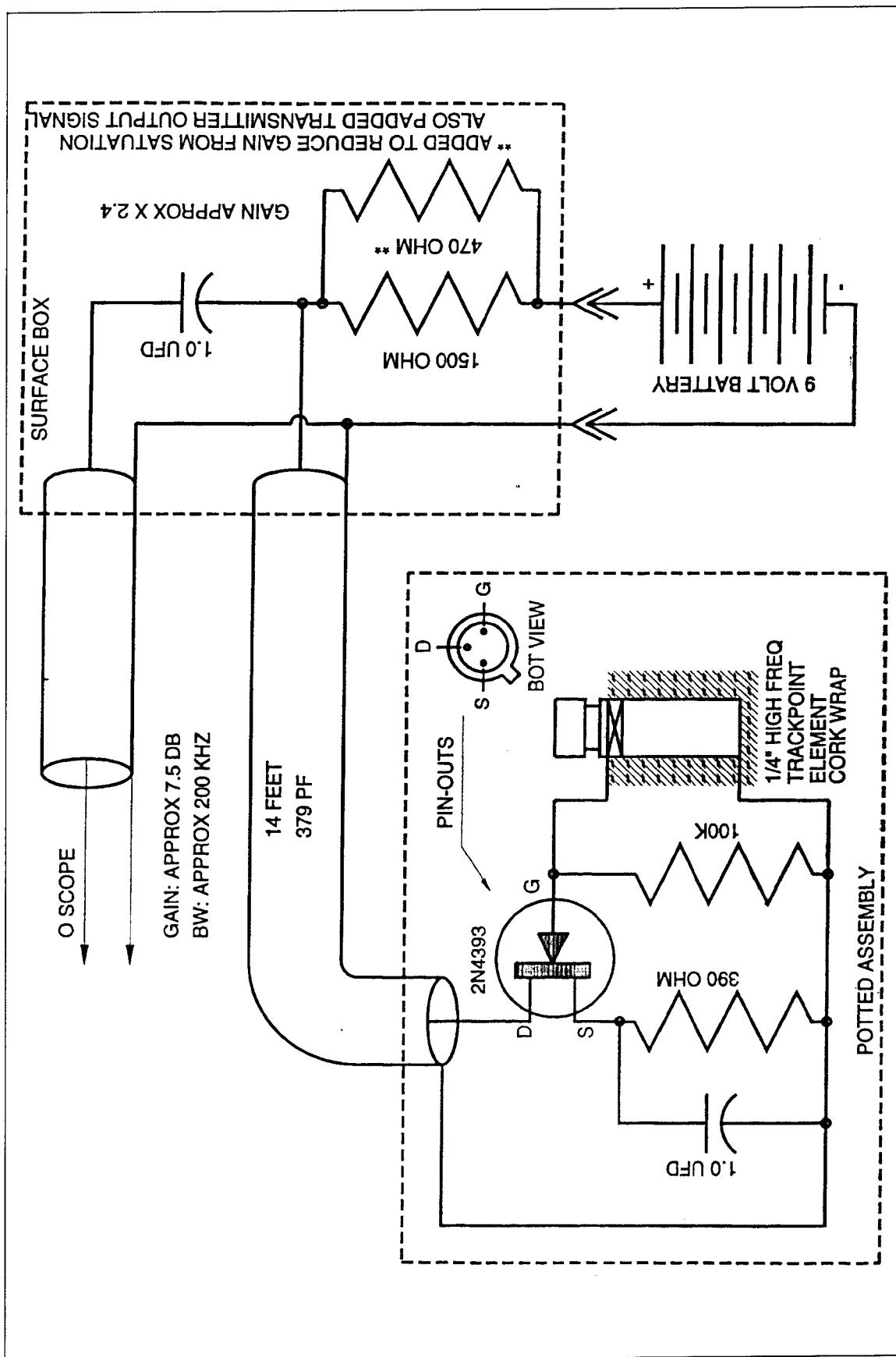


Figure A9. Receive array pre-amplifier for tank tests

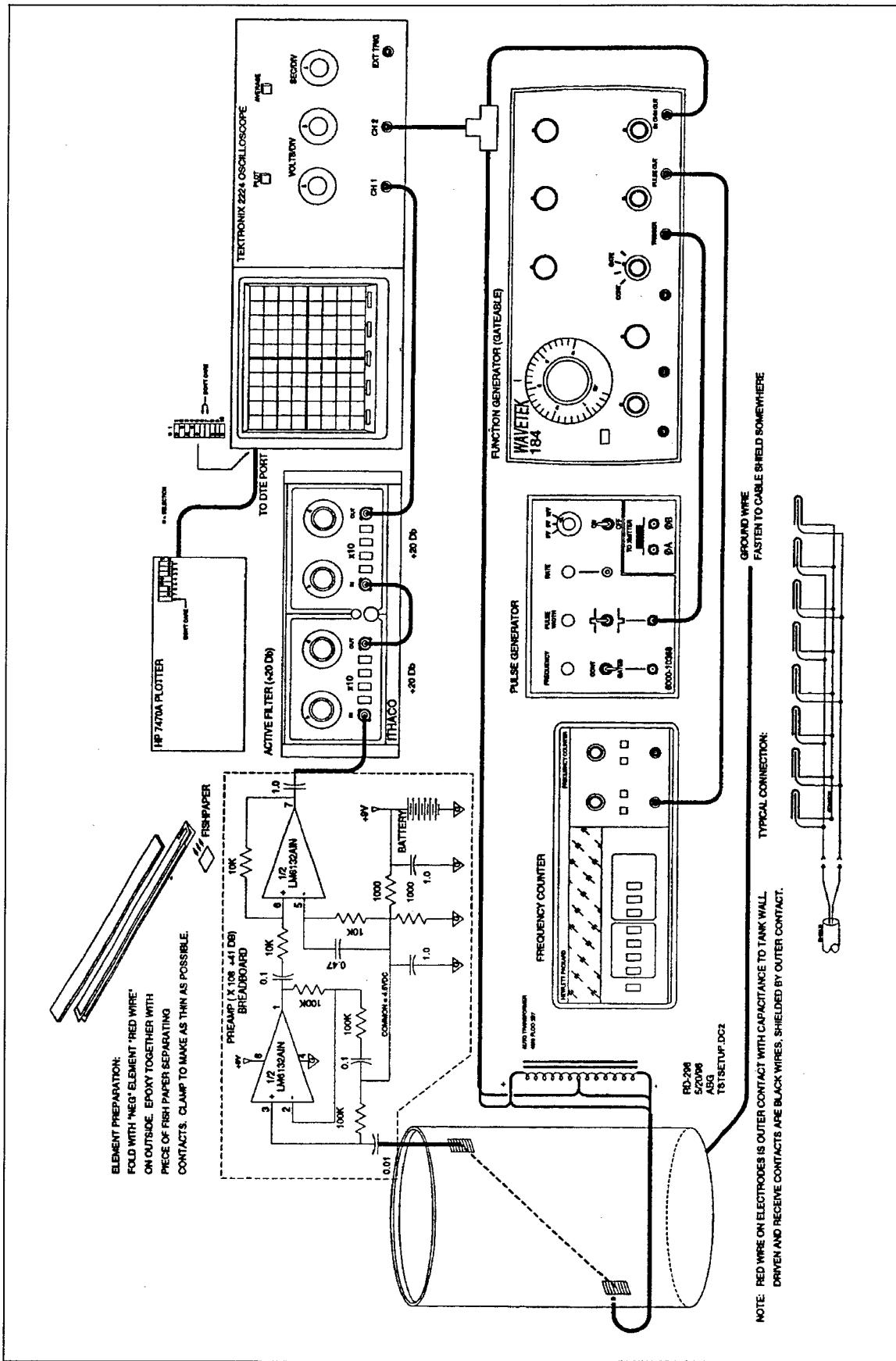


Figure A10. Path test setup block diagram

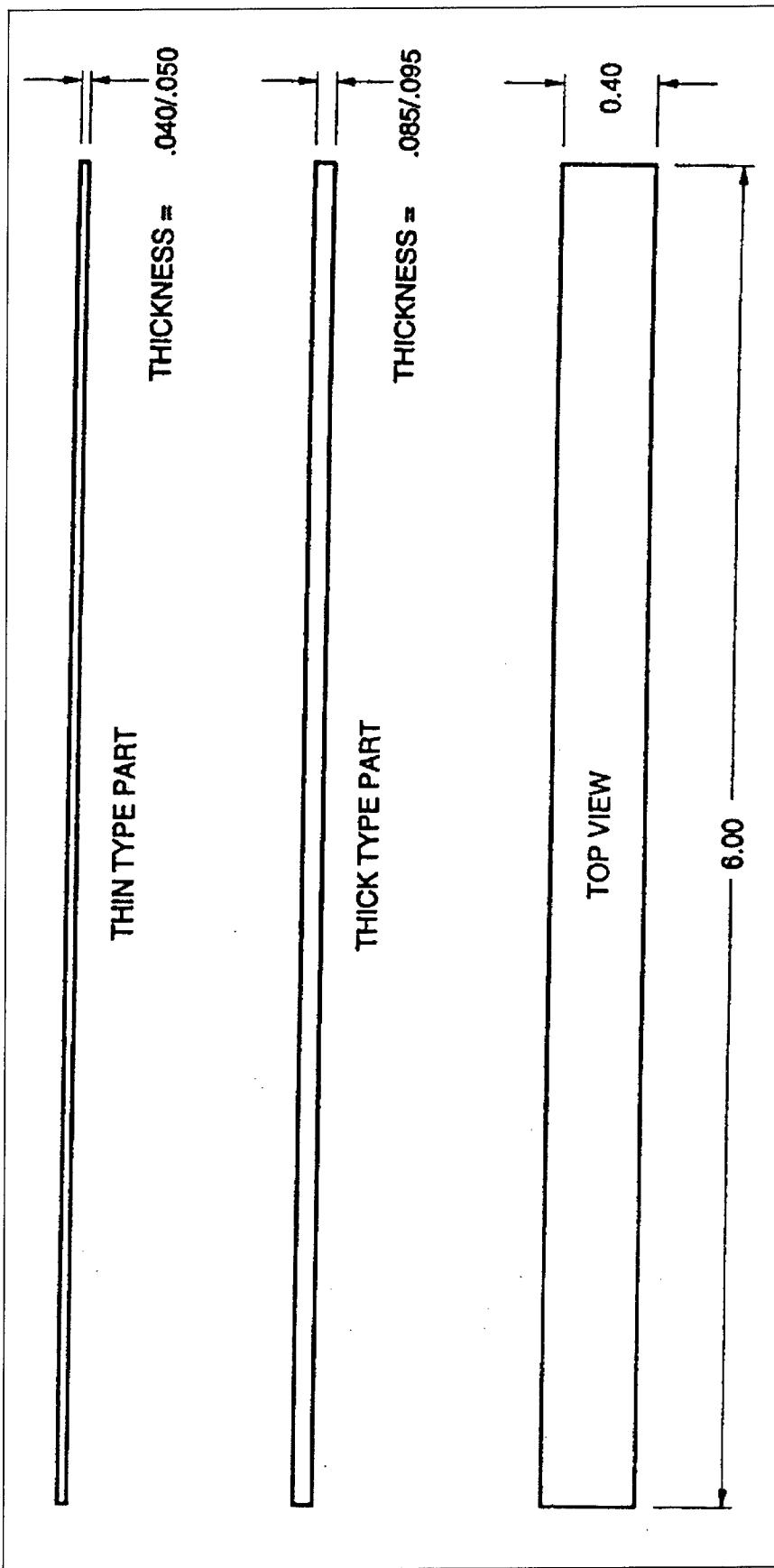


Figure A11. Details of lead strips used as backing in transducers

**Appendix B:
United States Patent
Number 5,228,347 Dated
July 20, 1993 Awarded to
F. C. Lowell and R. H. Lyon
Method and Apparatus for
Measuring Flow by Using
Phase Advance**



US005228347A

United States Patent [19]

Lowell et al.

[11] Patent Number: 5,228,347

[45] Date of Patent: Jul. 20, 1993

[54] METHOD AND APPARATUS FOR
MEASURING FLOW BY USING PHASE
ADVANCE

[75] Inventors: Francis C. Lowell, Falmouth; Richard H. Lyon, Belmont, both of Mass.

[73] Assignee: ORE International, Inc., Falmouth, Mass.

[21] Appl. No.: 781,016

[22] Filed: Oct. 18, 1991

[51] Int. Cl.⁵ G01F 1/66

[52] U.S. Cl. 73/861.28; 73/861.27

[58] Field of Search 73/861.27, 861.28, 195

[56] References Cited

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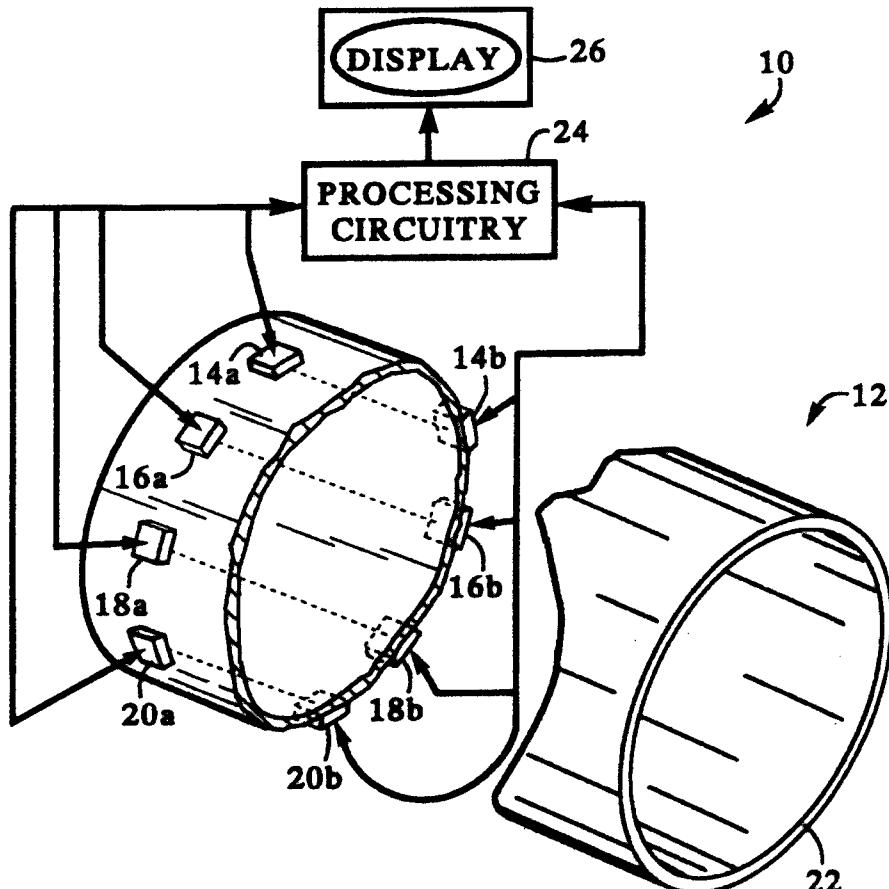
Re. 30,900 4/1982 Shih 73/861.27
4,144,753 3/1979 Larsen 73/861.27
4,462,261 7/1984 Keyes et al. 73/861.27
4,616,510 10/1986 Moore 73/861.27

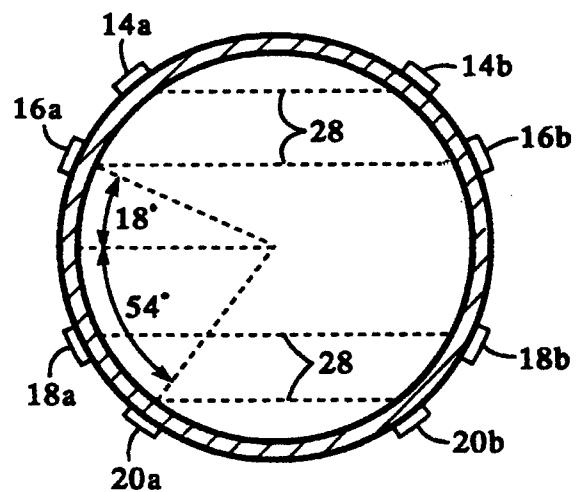
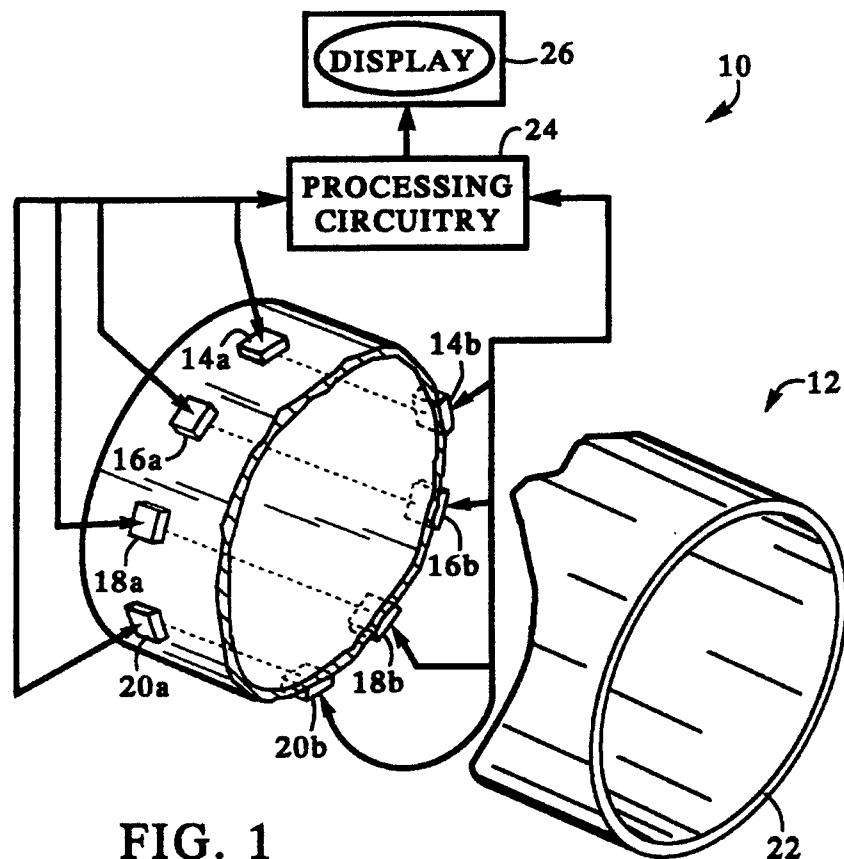
Primary Examiner—Donald O. Woodiel
Assistant Examiner—Elizabeth L. Dougherty
Attorney, Agent, or Firm—Cesari and McKenna

[57] ABSTRACT

A flow meter (10) employs phased arrays (14a, 14b, 16a, 16b, 18a, 18b, 20a, and 20b) of ultrasonic transducers mounted on the exterior of a pipe (12) to transmit and receive sound directed through paths that pass through the pipe interior. The flow meter (10) determines the rate of fluid flow through the pipe (12) by comparing the sound-propagation times for sound traveling the same paths in opposite directions. By driving the transducers as phased arrays, the flow meter (10) can employ sound-propagation paths that form angles to the normal to the interior pipe wall that exceed those dictated by Snell's law as applied to the relative propagation speeds in the pipe wall and the fluid.

18 Claims, 5 Drawing Sheets





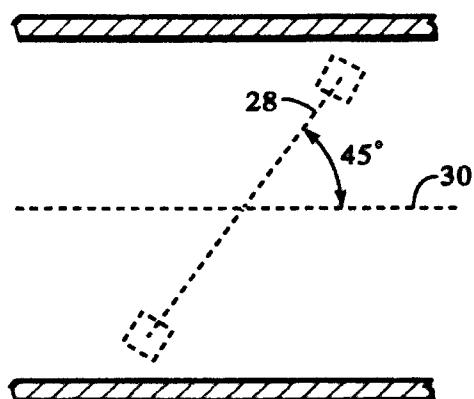


FIG. 3

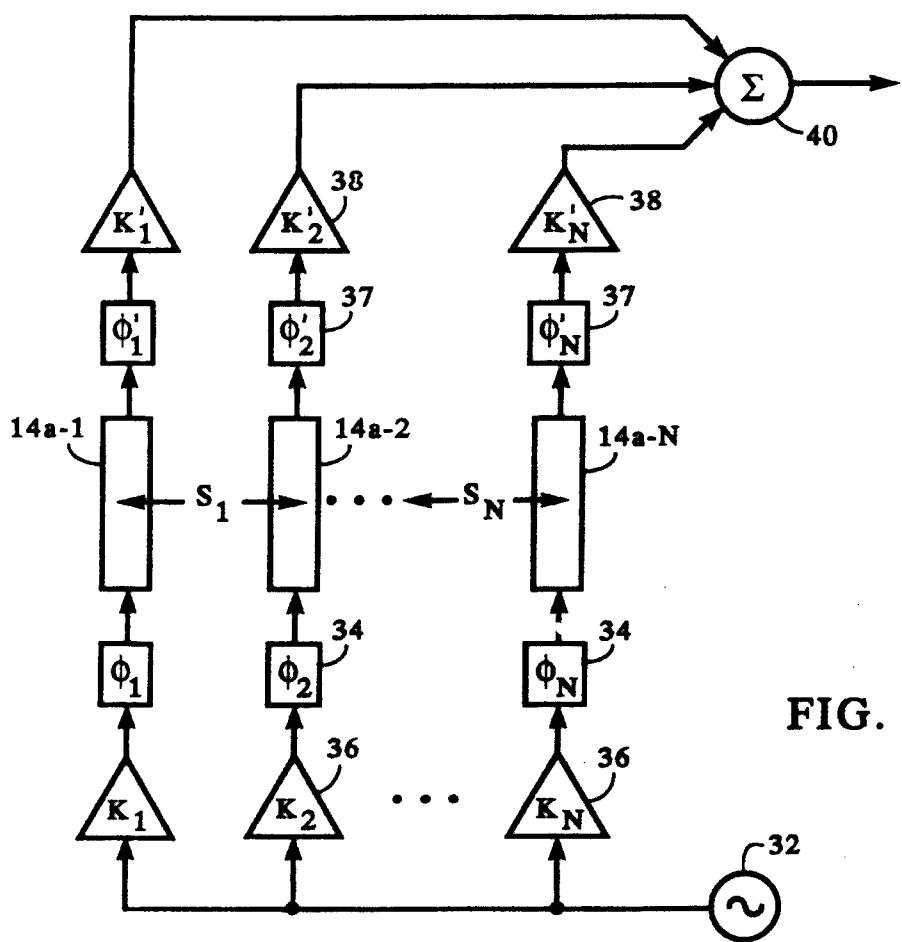


FIG. 4

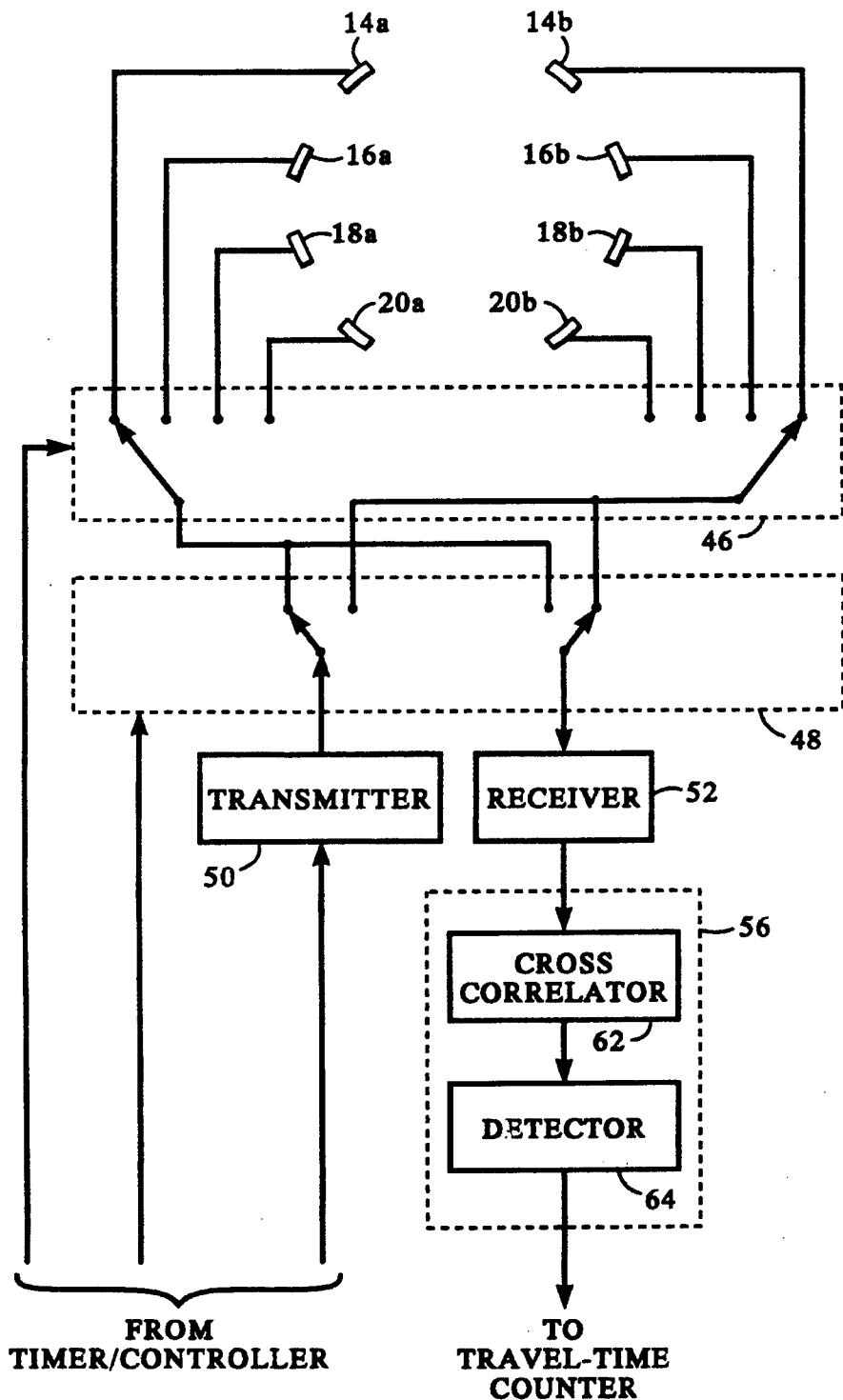


FIG. 5A

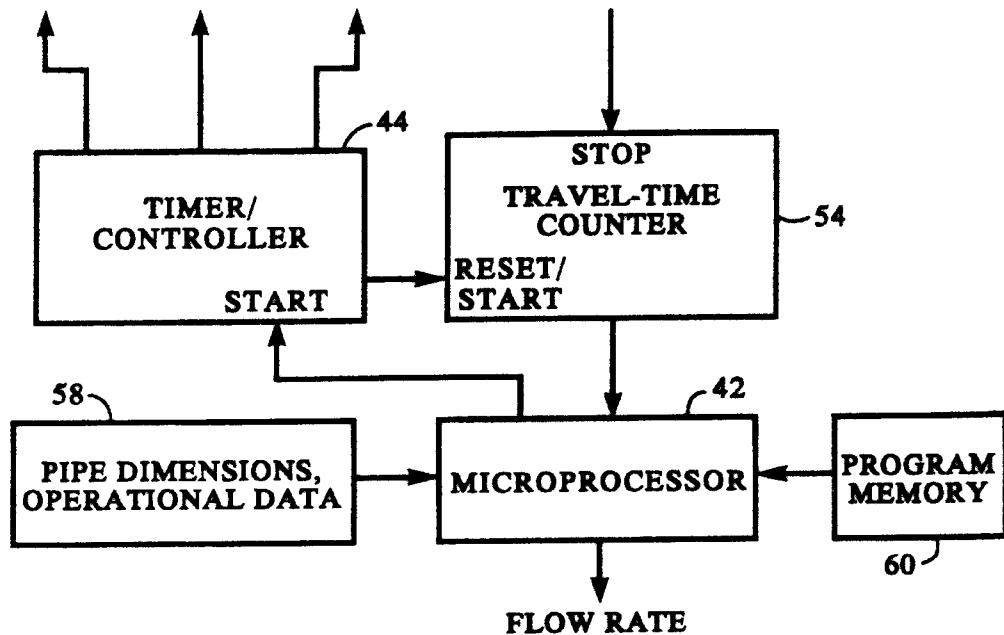


FIG. 5B

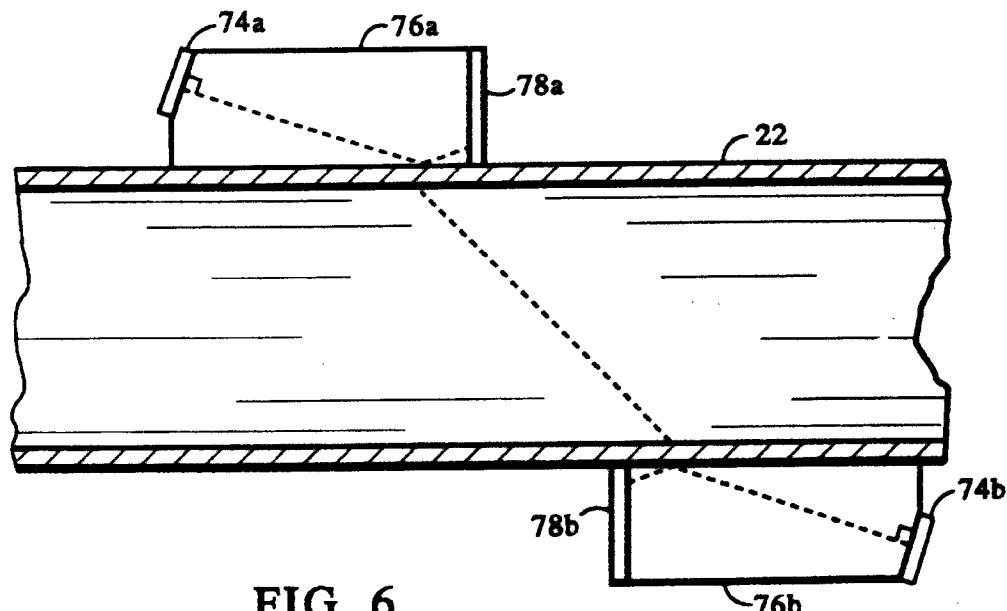


FIG. 6

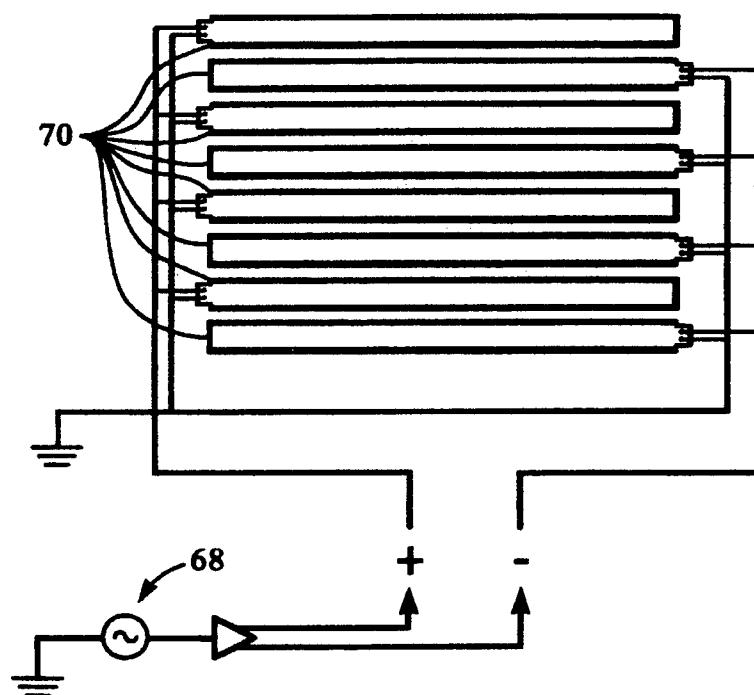


FIG. 7

METHOD AND APPARATUS FOR MEASURING FLOW BY USING PHASE ADVANCE

BACKGROUND OF THE INVENTION

The present invention is directed to sonic flow meters including ultrasonic flow meters.

A popular way of making a fluid-flow measurement (i.e., of determining the speed of a fluid or, more typically, its volume rate of flow) in a fluid conduit is to employ an ultrasonic flow meter. Such meters send sound in opposite directions through the same path and measure the transit times required for the sound propagation. If the path has a component in the direction of the fluid flow, the fluid flow causes a difference between the two transit times, and this difference is indicative of the fluid velocity. Integrating the axial component of the fluid velocity over the conduit cross section yields the flow rate.

In principle, one can perform this method by employing transducers that are coupled to the outside surface of the conduit wall, and in fact this approach—that is, of coupling the transducers to the conduit wall rather than using transducers actually in contact with the fluid itself—has significant advantages. Coupling the transducers to the exterior of the conduit avoids the need to de-water the conduit and drill through the conduit wall, as is necessary with a “wetted” transducer, i.e., one that is in direct contact with the fluid. In the case of, for example, conduits used for hydroelectric power plants, the economic loss that results from de-watering can be considerable.

Despite these advantages, it has often been necessary in the past to use wetted transducers instead. The reason for this is that, when an ultrasonic transducer element launches its output through a (usually) high-ultrasound-velocity conduit wall into the relatively low-ultrasound-velocity fluid within the conduit, Snell's law imposes a limit on the angle that the main lobe of the resulting diffraction pattern can form with the normal to the conduit wall. If a measurement path is to be used that significantly exceeds the Snell's-law limit, therefore, the received signal that results from that path tends to be dwarfed by signals received from other paths, and the measurement cannot be made accurately, if at all.

The resultant limitation to small angles would not be a problem if the fluid velocity were strictly axial and the shape of the velocity profile throughout the conduit cross section were known; so long as one knew the speed of sound in the fluid, the conduit cross-sectional area, and the angle that the sound path forms with the conduit axis, the flow-rate computation would be a straightforward matter, and the accuracy would be limited only by the time-measurement resolution.

But the fluid-flow direction is not always strictly axial, and the shape of its profile is rarely predictable. Since the flow direction is not strictly axial, part of the sonic transit-time difference can undesirably result from the non-axial fluid-velocity components, which do not contribute to the flow to be measured. The significance of this “cross-flow” error is greater when the non-axial component of the ultrasound path is large in comparison with the axial component, as it is at the path angles that are possible with prior-art externally mounted flow meters. Still, the cross-flow problem can be overcome by employing crossed sound-propagation paths.

The more-difficult problem results from the unpredictable nature of the velocity profile. To obtain high accuracy, one must measure the transit-time difference not for a single diametral path but rather for a plurality of chordal paths so as to “sample” the average velocities at various slices through the conduit cross section. This means that ultrasound would have to be introduced at an angle to the wall-surface normal even if no axial ultrasonic-path component were necessary. As was mentioned above, Snell's law places a limit on how large this angle can be in traditional externally mounted flow meters. For accurate measurements, therefore, it has been necessary in the past to resort to wetted-transducer flow meters.

SUMMARY OF THE INVENTION

The present invention overcomes the angle limitations of prior-art externally mounted flow meters by forming what we refer to as a “virtual phased array” on the interior conduit surface whose phase advance is such as to form a beam having a main lobe directed at an angle that exceeds the angle of total internal reflection. Either the transmitter, the receiver, or both employ phased arrays.

In the case of a transmitter, the virtual array is typically created by driving the conduit's exterior surface with sound whose combination of frequency and phase advance corresponds only to an evanescent (“forced”) wave in the conduit material. Because the sound takes the form of an evanescent wave in the conduit material, it decays at least exponentially as it travels away from the transmitter through the conduit-wall material, and significant sound amplitude at the conduit wall's interior surface is present only opposite the transducer array. In that region, however, the vibrating wall forms a “virtual phased array,” whose phase advance is determined by that at the exterior surface and concentrates the majority of the sound power (or at least of that part of the sound power that reaches the complementary transducer at the time of measurement) in a beam centered on the measurement path. Thus, the transmitting transducer array causes relatively little sound that can be reflected or refracted to the receiving transducer from directions other than that of the intended measurement path.

In the case of a receiver, the operation is just the reciprocal. This makes the receive signal sensitive to sound from the path and relatively insensitive to sound from other directions.

Accuracies significantly higher than those of prior-art externally mounted flow meters can thereby be achieved.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a simplified isometric view of a flow conduit showing the placement of transducers for an ultrasonic flow meter;

FIG. 2 is an end view of the conduit also showing the transducer-placement geometry;

FIG. 3 is a plan view of the conduit, also depicting the transducer-placement geometry;

FIG. 4 is a diagram conceptually depicting phased-array operation;

FIGS. 5A and 5B together form a block diagram of a typical flow meter of the type that might employ the teachings of the present invention;

FIG. 6 is a cross-sectional view of an alternate embodiment of the present invention; and

FIG. 7 is a diagram of a transducer array and simple phasing arrangement that we have employed to demonstrate the principles of the present invention.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

FIG. 1 depicts a flow meter 10 for measuring the flow of a fluid through a pipe or other conduit 12. For this purpose, four pairs of transducers 14a and 14b, 16a and 16b, 18a and 18b, and 20a and 20b are arrayed around the exterior of the conduit wall 22.

To determine the rate of flow, processing circuitry 24 drives transducer 14a and measures the delay between the time at which transducer 14a is driven at the time at which transducer 14b receives the resulting sonic signal. In principle, the frequency of the sound can be within, above, or below the audible range, but practical flow meters almost invariably employ ultrasonic frequencies.

The processing circuitry 24 then reverses the process, driving transducer 14b and receiving the resulting signal at transducer 14a. If the displacement vector between transducers 14a and 14b has a component in the direction of fluid flow between the transducers, the travel-time measurement taken in one direction will differ from that taken in the other direction, and the difference will be an indication of the component of the flow velocity along the path between the transducers.

A single pair of transducers can thus give a flow measurement, and it will become apparent that the teachings of the present invention can be embodied in such a single-path meter. Since flow velocity is not in general uniform, however, the processing circuitry 24 of the illustrated embodiment also performs similar operations by using further transducer pairs 16a and 16b, 18a and 18b, and 20a and 20b. By applying well-known numerical-integration curve-fitting techniques to these velocity "samples," the processing circuitry 24 determines the rate of flow through the pipe 12, and it transmits signals indicative of the computed flow rate to a display 26 or to some process-control circuitry.

To obtain the best accuracy from the known approximation techniques, it is important that the paths 28 between the transducers be judiciously selected. For "Chebyshev" spacing of a four-transducer-pair flow meter, the projections of the paths between transducers 14a and 14b and between transducers 20a and 20b onto a plane perpendicular to the pipe axis form angles of 54° with the normal to the pipe wall, while the corresponding angles for the other two paths is 18°. "Chordal" measurement thus necessitates orienting the paths 28 at significant angles to the pipe-wall normal.

Moreover, the angles are even greater than is apparent from FIG. 2 because of the need to obtain a significant axial path component. In the illustrated embodiment, this is achieved by angling the paths 28, as FIG. 3 indicates, so that they lie in a plane that forms a angle of 45° with the pipe axis 30. Accordingly, the angles that the paths form with the normals are actually 66° and 48°. To direct the sonic beam into such paths, the transducers are phased arrays. For instance, transducer 14a may consist, as FIG. 4 illustrates, of a plurality of transducer elements 14a-1, 14a-2, . . . , 14a-N, separated by spacings s₁, s₂, . . . , s_{N-1}. Each is driven by a respective signal generated by subjecting the output of a common source 32 to respective phase shifts represented by phase-shift blocks 34, possibly with some relative weighting introduced by respective amplifiers (or attenuators) 36. For reception, similar phase-shifting—and

possibly similar weighting—represented by blocks 37 and 38 of FIG. 4 are applied to the received signals, and an analog adder 40 combines the results so that signals from the desired path add constructively while those from other directions interfere destructively. This increases power and sensitivity in the desired path while reducing them in other paths.

As is conventional in phased arrays, transducers spaced apart by a separation s_k along an array axis steer the resultant beam to an angle θ with the normal to that axis by operating out of phase with each other by a phase advance $\phi_k = s_k k \sin \theta$, where k is the wave number (in radians/unit length) of the resultant propagating wave. In a conventional externally mounted flow meter, this is accomplished by first launching a traveling wave in the conduit wall whose direction θ_w is related to the desired direction θ in the fluid by Snell's law; i.e., $\theta_w = \sin^{-1}[(k_f/k_w)\sin\theta]$, where k_f and k_w are the wave numbers in the fluid and conduit wall, respectively.

The maximum such angle θ_f in the fluid obtainable with this approach is the critical angle θ_c , which results from the maximum angle (90°) in the conduit wall, i.e., $\theta_c = \sin^{-1}(k_f/k_w)$.

Now assume that the pipe 12 is made of steel, the fluid inside is water, and the water temperature is such that the speed of sound in the water is 1450 m/sec. Even if the meter employs the (relatively slow) shear mode of propagation through the pipe wall, the propagation speed in the pipe wall is still on the order of 3140 m/sec, so the maximum Snell's-law angle is 28° with the normal to the wall surface. In a conventional flow meter, therefore, it would not be practical for the paths between the transducers to exceed this angle by more than about 1°, as they do in FIGS. 2 and 3. In accordance with one embodiment of the present invention, however, sound communication can be performed effectively by way of the indicated paths 28 because one or both transducers of each transducer pair is an array of transducer elements driven or sensed in a phased-array fashion so as to steer the resultant beam to an angle considerably greater than the Snell's-law angle.

That is, the phase advance ϕ_k exceeds $s_k k_w$ in our method. The fundamental spatial frequency imposed upon the exterior conduit-wall surface thus exceeds the spatial frequency $2\pi/k_w$ of a traveling wave in the wall, and theory tells us that such a boundary condition in a semi-infinite medium yields only an evanescent wave, i.e., one in which the pressure and motion variations have such phase relationships that the wave carries no average net power and decays exponentially with distance from the source. But we have recognized that a "virtual phased array" having such a high phase advance can nonetheless be used for externally-mounted flow-meter operation, because operation of the phased array at the outer wall surface causes a phase advance at the inner wall surface the same as that at the outer wall surface (if parallel wall surfaces are assumed) even when that phase advance corresponds to only an evanescent wave in the conduit wall. The result is a traveling wave in the fluid whose angle with the normal to the conduit wall exceeds the Snell's-law limit and thus yields a sound path in the fluid whose axial component is, as desired, relatively large. The reason why power is transmitted through the pipe wall despite the evanescent-wave propagation in it is that the inner pipe-wall surface imposes a second boundary condition, which requires superimposition of a reverse evanescent wave on the originally launched wave in such a manner that

the resultant phase relationships in the conduit wall yield a net power flow.

Of course, such an approach can be avoided if the disparity between refractive indices is not so great. For example, one might conceive of a reasonably accurate two-path, 65° plane-angle Chebyshev chordal-measurement scheme for a refractive-index ratio of, say 1.5. For ratios greater than this, or at least greater than 1.62, however, we believe that the present invention yields significant advantages.

FIGS. 5A and 5B depict apparatus of the type that might be employed to carry out the teachings of the present invention in a flow meter. When a measurement is to be made, a microprocessor 42 commands a timer/controller 44 to begin operation. That controller 44 operates a path selector 46 and direction controller 48 to connect the appropriate transducers to a transmitter 50 and a receiver 52. The controller then triggers the transmitter 50, which generates the several phase-offset signals and applies them through the direction controller 48 and path selector 46 to the elements of the particular transducer to be driven. When the timer/controller 44 triggers the transmitter 50, it also causes a travel-time counter 54 to reset and begin counting. The timer/controller 44 then turns off the transmitter 50 while the travel-time counter continues measuring the time that has elapsed since the transmitter 50 caused the one of the selected transducers to transmit the ultrasonic signal.

The receiver 52 eventually receives the resultant ensemble of signals from the other selected transducer. The receiver 52 adds the ensemble together in the appropriate phase relationship and applies the resultant sum signal to processing circuitry 56, whose output is a pulse that stops the counter 54 when the sum signal 35 meets certain (amplitude-related) criteria. The counter 54 applies the resultant travel-time measurement to the microprocessor.

The operation is then repeated with the direction controller 48 switched to its other state to produce a second travel-time measurement. By comparing the two travel-time measurements and taking into account the path dimensions and other operational data stored in a memory 58 provided for that purpose, the microprocessor 42 operates under control of a program in a memory 45 60 to compute a fluid velocity for the path just measured.

By repeating this operation with the path selector 46 in different states, the microprocessor 42 computes the flow rate by multiplying the pipe's cross-sectional area 50 by a sum of the computed velocities weighted to achieve, say, a Chebyshev approximation, as will be familiar to those skilled in the art.

As was mentioned above, the different paths form different angles with the normals to the wall surface at the points at which they intersect it. For many arrays, these differences will be substantial; i.e., if the angle for one of the paths is centered in an array's main lobe, the angle for the other will be displaced from the center by enough that a measurement for that path cannot be 60 made effectively with an identical (and identically driven) array.

In some embodiments of the invention, therefore, the frequency (or, as will be described below, frequency range) of the transmitter will be changed when the path selector 46 changes so as to permit identical arrays to be used for paths that form different angles with the pipe-wall normal. The same effect can be achieved by using

different phase advances per transducer element. Identical arrays can be used even without changing frequencies or phase advances if the angles formed with the pipe axis by the paths' plan-view projections so differ as to yield equal angles with the pipe-wall normals at the paths' points of intersection.

In certain applications, accommodations may need to be made for the fact that sound waves in the pipe wall are evanescent, "forced" waves rather than propagating, "free" waves. Specifically, evanescent waves decay exponentially with distance, as was mentioned above. While this yields the desirable effects mentioned above, it also affects the interior-wall amplitude immediately opposite the array. This is particularly true, of course, for relatively thick pipe walls. For such walls, it will ordinarily be necessary to use an ultrasonic frequency significantly below those normally used for flow measurement; decreasing the frequency tends to reduce the rate of attenuation.

Everything else being equal, however, frequency reduction also reduces the resolution with which the travel time can be measured. To overcome this problem, one can appropriately encode the transmitted signal and use a filter on the receiving end that is matched to the selected encoding. Such techniques are typically used in radar, sonar, medical ultrasound, and related arts for pulse compression and thus time-resolution enhancement.

One of the most common types of encoding, of course, produces a "chirp" signal, i.e., a signal whose instantaneous frequency increases or decreases with time. For instance, the transmitter 50 could be a chirp transmitter that transmits a two-millisecond pulse having a frequency that sweeps from 80 kHz to 120 kHz. Ordinarily, the signal that the receiver 52 generates in response will have a duration somewhat in excess of that of the transmitted signal because the ensemble that the receiver 52 receives is generated by elements that receive their signals at slightly different times.

To a minor extent, this undesirable spreading of the signal can be reduced by imposing actual time delays to introduce the transmitting transducer elements' phase shifts and thus staggering the times at which they begin transmitting. In most cases in which duration reduction is needed, however, more reduction than this is required. Obtaining this reduction in output-signal duration—and the resultant increase in time-measurement resolution—is the purpose of the matched filter provided by the signal-processing circuitry 56.

As an example, FIG. 5A depicts the signal-processing circuitry 56 as having the form of a cross-correlation circuit 62 and a detector 64. The cross-correlation circuit 62 receives a replica of the transmitted signal and cross-correlates this with the received signal. The resultant output is minor except at a correlation delay equal to the travel time, when the two signals "match" and produce a large output signal. The resultant correlator output pulse is accordingly significantly compressed in time in comparison with the output of the receiver 52 if the correlation records are long enough. The detector 64 produces the counter-stopping output pulse when the correlator output exceeds a predetermined minimum. In this way, the travel-time resolution can be greatly increased.

Other types of encoding and matching, well known to those skilled in the art, can also be used; actual digital correlation is not necessary. For instance, one type of chirp-signal generation involves applying a very-short-

duration DC pulse to a dispersive delay line, possibly before or after band-pass filtering. Since different frequency components traverse the delay line at different speeds, the resultant signal is a chirp signal. Matching at the receive side can then be accomplished simply by applying the received signal to a delay line whose dispersion curve is the reverse of that of the transmitter's delay line. This and other well-known approaches can be employed with the present invention.

As those skilled in the art are also aware, although elements in most phased arrays are spaced equally both in physical position and in phase, this is not always so, and it may be desirable in chirp-signal or other encoded versions of the present invention to employ non-uniform spacing. For a given spacing, for instance, the main-lobe direction depends on frequency if no adjustments in phase offset are made to counteract the direction change. Since such adjustments will in many situations be considered too complex, it may be preferable to provide the transducer elements in, for instance, a logarithmic spacing so that, as the instantaneous frequency of the chirp signal changes and the main lobe of the beam from one part of the array moves away from the direction of the path between the transmitting and receiving transducers, the beam from another part of the array becomes directed into that path.

In other situations, on the other hand, the adjustment of phase advance for frequency is not at all complex. For example, consider the arrangement depicted in FIG. 6. FIG. 6 depicts one pair of transducers 74a and 74b.

Each transducer 74a or 74b can in principle be a single element, although in practice it may be found convenient to employ a plurality of elements driven or sensed in phase. Each transducer is mounted on a respective low-refractive-index block 76a or 76b, which is mounted to the exterior surface of the pipe wall 22. Each transducer is mounted at such an angle that it launches waves whose angle with the normal to the pipe wall 22 exceeds the angle of total internal reflection in the block. In other words, the launched waves result in a phase advance at the block-wall interface that causes the desired evanescent waves in the pipe wall 22. Acoustically non-reflective absorbers 78 prevent the reflected sound from interfering with the intended signal at the exterior wall surface.

The angle at which the transducers are mounted is such that the resultant phase advance at the interior wall forms a beam directed at the complementary transducer; if the block 76 had the same index of refraction as the water inside the pipe, for example, the transducers would be angled so that the sound angle within the block is the same as the intended sound angle in the water. In the FIG. 6 arrangement, the phase advance at the block-wall interface changes automatically with the frequency at which the transducer is driven, and the change in phase advance maintains the desired angle independently of frequency.

To test the principle of transmission on which the present invention is based, we performed experiments on a vertically oriented three-eighths-inch-thick water-filled steel pipe that was six feet long and four feet in diameter. We performed two sets of experiments. The first involved only a single array. We drove the array 65 and measured the resulting signal amplitudes at various physical angles by raising and lowering along the pipe axis a hydrophone immersed in the water.

In this experiment, an eight-element array of transducer elements was axially spaced along the exterior surface of the pipe wall. Each array element comprised a 15-cm × 1.9-cm strip of 52-micron-thick polyvinyl difluoride (PVDF) folded along its length. The eight resultant folded pieces were attached with epoxy adhesive to the pipe exterior on half-inch centers. A single layer of 120-micron-thick lead backing was attached by epoxy to each element. Of course, other types of transducers can be employed, too, but the PVDF approach has certain advantages: a transducer array can readily be imprinted onto a single PVDF sheet and applied in that form to the exterior of the conduit.

To produce the phased-array relationship, the transducer elements were driven in the manner depicted in FIG. 7. Specifically, a signal generator 68 was operated in a "bridge" mode to generate opposite-polarity signals, which were applied to alternate elements 70. That is, the phase advance per element employed in the array was 180°. Of course, this resulted in two main lobes, but this is acceptable for most flow-meter applications, since the other transducer is located in only one of the lobes, and the other lobe is so directed that ordinarily very little of its sound could be reflected in such a manner as to interfere with the measurement. Accordingly, the phase-delay circuitry can be as simple as that depicted in FIG. 6. For increased efficiency, of course, more-complicated phasing and array design may be preferable so as to focus the sonic power into a single main lobe.

With the illustrated arrangement, we drove the array at frequencies of 75 kHz, 100 kHz, and 125 kHz. The resultant main-lobe angles were 31°, 42°, and 50°, respectively. Such angles result in flow-direction components that are appropriate for chordal-flow-meter operation. Half-power beamwidths for these frequencies ranged between about 6.5° and about 17°, the greatest beamwidth occurring at around 100 kHz.

We also performed a two-sided experiment, in which we used similar transducer arrays positioned at opposite ends of a path through the pipe axis and forming an angle of 45° with it. That is, the transmitter was driven as illustrated in FIG. 6, while sums of the odd and even transducer-element outputs at the receiver end were respectively applied as the inverted and non-inverted inputs to a differential amplifier. With this arrangement, a 7.1-volt-rms input yielded a 0.7-millivolt-rms output at the peak frequency of 95 kHz. The half-power bandwidth was 17 kHz.

It is thus apparent that the teachings of the present invention provide a way of achieving the high accuracy that chordal methods provide without suffering the difficulties in mounting that usually attend such methods. The present invention thus constitutes a significant advance in the art.

We claim:

1. In the method of measuring fluid flow by transmitting sound from outside a fluid conduit in opposite directions through a sound path that extends through the conduit wall and through a fluid within the fluid conduit, detecting from outside the fluid conduit the sound transmitted through the path, measuring the time between transmissions and receptions so as to determine travel times in the opposite directions, determining the flow of the fluid from the difference between the travel times, and generating a signal indicative thereof, the improvement wherein at least one of the steps of transmitting and receiving comprises transmitting or receiv-

ing with a phase advance at the exterior conduit-wall surface that corresponds to an evanescent wave in the wall of the fluid conduit at the frequency of the transmitted sound.

2. A method as defined in claim 1 wherein the angle formed by the path in the fluid with the normal to the interior surface of the conduit exceeds the inverse sine of the ratio of the speed of sound in the fluid to the speed of sound in the wall of the conduit by at least 1°.

3. A method as defined in claim 2 wherein the angle formed by the path in the fluid with the normal to the interior surface of the conduit exceeds 29°.

4. A method as defined in claim 1 wherein the ratio of the speed of sound in the conduit wall to that in the fluid exceeds 1.5.

5. A method as defined in claim 1 wherein at least one of the steps of transmitting and receiving comprises one of transmitting and receiving by means of a phased array of sonic transducers.

6. A method as defined in claim 5 wherein the transmitting and the receiving steps are both performed by means of phased arrays of sonic transducers.

7. A method as defined in claim 5 wherein the angle formed by the path in the fluid with the normal to the interior surface of the conduit exceeds the inverse sine of the ratio of the speed of sound in the fluid to the speed of sound in the wall of the conduit by at least 1°.

8. A method as defined in claim 7 wherein the angle formed by the path in the fluid with the normal to the interior surface of the conduit exceeds 29°.

9. A method as defined in claim 7 wherein both the transmitting and the receiving steps are performed by means of phased arrays of sonic transducers.

10. A method as defined in claim 5 wherein the ratio of the speed of sound in the conduit to that in the fluid exceeds 1.5.

11. A method as defined in claim 5 wherein:

A) the method comprises making the travel-time determination for each of a plurality of different paths; and

B) the step of determining the flow comprises determining the volume rate of flow from the differences between the travel times in the plurality of paths.

12. A method as defined in claim 11 wherein:

A) the angle formed by the projections of a first of the paths and the axis of the conduit onto a plane parallel to both is substantially different from the angle formed by the projections of a second of the paths and the axis of the conduit onto a plane parallel to both; and

B) the angles formed by the first and second paths with the normals to the interior surface of the conduit at the paths' respective intersections therewith are substantially equal,

whereby the frequencies and transducer arrays employed for the two paths can be identical.

13. A method as defined in claim 11 wherein:

A) the angles formed by first and second paths with the normals to the interior surface of the conduit at

the paths' respective intersections therewith are substantially different; and

B) the ratio of frequencies of sound propagation in the two paths is substantially the reciprocal of the ratio of the tangents of the two paths' angles with their respective normals,

whereby the transducer arrays and phase advance used for the first and second paths can be identical.

14. A method as defined in claim 11 wherein:

A) the angles formed by first and second paths with the normals to the interior surface of the conduit at the paths' respective intersections therewith are substantially different; and

B) the ratio of the phase advances applied to the transducer arrays used for the first and second paths is substantially equal to the ratio of the tangents of the two paths' angles with the normals to the interior surface of the conduit at those paths' respective intersections therewith,

20 whereby the transducer arrays and frequencies used for the first and second paths can be identical.

15. A method as defined in claim 1 wherein:

A) the method comprises making the travel-time determination for each of a plurality of different paths; and

B) the step of determining the flow comprises determining the volume rate of flow from the differences between the travel times in the plurality of paths.

16. In a flow meter comprising sound transmission and reception means, adapted to be placed at opposite ends of a sound path that extends through a fluid, for transmitting sound in opposite directions through the sound path and detecting its arrival at the ends thereof and further comprising means for measuring the travel times required for the sound to traverse the sound path, for computing the difference there between, and for generating therefrom an indication of the flow of the fluid, the improvement wherein at least one of the sound transmission and reception means comprises means for performing transmitting or detecting with a phase advance at the exterior conduit-wall surface that corresponds to an evanescent wave in the wall of the fluid conduit at the frequency of the transmitted sound.

17. A flow meter as defined in claim 16 wherein at least one of the sound transmission and reception means comprises:

A) an array of transducer elements; and

B) circuitry for performing, for each direction of sound transmission, at least one of the sound transmission and detection by respectively driving the array elements as a phased array or combining the array elements' electrical outputs in a phased-array relationship.

18. A flow meter as defined by claim 17 wherein the circuitry performs the sound transmission by driving the array elements as a phased array and performs the sound detection by combining the array elements' electrical outputs in a phased-array relationship for both directions of sound transmission.

* * * *

Appendix C:
Report Dated 15 August 1991
From R. H. Lyon Corporation
Experimental Results On the
Design of an Externally
Mountable Acoustic Flow Meter

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MEMORANDUM

To: Pete Lowell; ORE
From: S. Arzoumanian, R. Lyon, B. Starobin; RH Lyon Corp
Subject: Externally Mounted Acoustic Flow Meter Design
Date: 15 August, 1991

The purpose of this memorandum is to report on the experimental results of our latest effort regarding the design of an externally mounted acoustic flow meter.

The overall results of our experimental effort are encouraging. For a set of experiments performed in the frequency bandwidth of 50-150 kHz efficiency levels of up to -80 db were observed. Signal to noise ratios were also quite satisfactory. Although we have confirmed most of the characteristics of externally mounted arrays on pipe sections that were anticipated in our analytical studies, the scope of this report does not permit us to elaborate in detail on these correlations.

EXPERIMENTAL SETUP, PROCEDURE AND RESULTS

For this phase of the project, all experiments were performed on a 3/8 inch thick, 6 ft tall and 4 ft in diameter capped steel pipe section filled with treated water. Figure 1 is a photograph of the general experimental setup.

Two major sets of experiments were conducted. The first consisted of a series of reciprocal experiments between a hydrophone immersed into the liquid and an eight element array mounted on the exterior of the tank. Measurements regarding the properties of the array (i.e., efficiency, linearity with driving voltage, steering angle, and main lobe beamwidth) as an acoustic source/receiver at various operating frequencies were performed at this stage.

The second set of experiments consisted of sending and receiving signals between two identical arrays on opposite sides of the tank. The radiation angle and optimum frequency were fixed for these tests and most of the analysis concentrated on studying the properties of the receiver signal including rise time and pulse to pulse consistency of the receiver signal. The effect of free waves in the pipe wall on the reception of the water transmitted signal was another area of inquiry.

EXPERIMENT I:

For this experiment, an 8 element array was installed near the bottom of the tank. Standard size PVDF strips (6in x 0.75in x 52micron), folded along their length, were attached to the exterior of the pipe section 0.5 inches apart (center to center) using epoxy adhesive. A single layer of lead backing (1/20 inches thick) was epoxied to each element. Figure 2 is a photo of the source array.

Through a stereo power amplifier, the array was fed with short pulses from an HP signal generator. The required phase relationship between the elements was achieved by operating the amplifier in "bridged" mode and connecting adjacent elements to outputs of opposite polarity. The pulses were 14 cycles long and 35 msec apart. The driving voltage level was kept at 7 V rms for most experiments.

A hydrophone was immersed into the liquid in order to investigate the characteristics of the source signal. The experimental setup is sketched in Figure 3a and the findings are presented below.

Directivity: At each operating frequency the hydrophone was maneuvered into the main lobe of the radiating signal and its position recorded. The steering angles for a few frequencies of interest were:

- *40 degrees @ 75 KHz
- *48 degrees @ 100 KHz
- *59 degrees @ 125 KHz

The half power beamwidths and bandwidths of the main lobe as measured on the axis of the tank are graphed in Figure 4ab. Notice the peaking behavior around 100 kHz. We believe that an acoustic focusing/defocusing effect is taking place there. Additional work might be required to determine whether or not phenomena of this type would influence any design considerations.

System efficiency: For given operating frequencies, the efficiency vs frequency of a source/receiver system made of similar arrays and positioned at their optimum angles was estimated by conducting a pair of reciprocal experiments (schematized in Figure 3ab). In Experiment A the array, acting as a source, was driven by the usual voltage (7 V rms) while the hydrophone, located in the main radiation lobe at the particular operating frequency, recorded the SPL. In experiment B, the hydrophone held at the same location was used as an acoustic emitter producing a comparable SPL at the array. There, the signals coming out of elements of opposite polarity were fed into a differential amplifier, filtered and recorded. An efficiency value re 1V/V was then obtained by compiling the results of these 2 experiments. This process was

repeated for a series of frequencies; the results are plotted in Figure 5.

The behavior of this curve confirms our theoretical predictions regarding the dependence of radiation efficiency on grazing angle and operating frequency. It may be recalled that transmission loss through the pipe wall increases with frequency but decreases with grazing angle. At low frequencies, it is the attenuation due to the low grazing angle that dominates. At high frequencies, the grazing angles are large and it is the attenuation effect associated with rising operating frequencies that takes over. In the mid range, the trade off between the tendencies appears to result with an efficiency maxima.

SPL in tank: Figure 6 shows as a function of frequency, the sound pressure level in the main lobe where it intersects the axis of the tank. The values are for an operating amplitude of 7 V rms. The SPL was found to be proportional to the input voltage for a wide range of amplitudes. A typical time domain hydrophone trace is plotted in Figure 7.

EXPERIMENT II:

For this experiment, a second eight element array was installed near the top of the tank across from the first. Figure 8 is a photograph of this array. The two arrays were positioned such that the line joining their centers intersected the cylindrical axis of the tank and formed a 45 degree angle with the horizontal. The bottom array was used as a source and the top array as a receiver in all of these experiments.

The source array was driven as in Experiment I; pulses were 14 cycles long and 35msec apart. The frequency at which the receiver signal peaked (i.e., the source was radiating at 45 degrees) was found to be 96 kHz. All of Experiment II's tests were conducted at this frequency.

As shown in Figure 9ab, two different configurations were used for wiring the receiver leads. In the first, only the 2 adjacent elements at the center of the array were used. Their outputs were fed into a differential amplifier, bandpass filtered, amplified by 60 db and viewed on an oscilloscope. In the second, all 8 elements were used with alternating ones connected in parallel. They were again fed into a differential amplifier, bandpassed, amplified and viewed in the same manner as the first. A typical time domain receiver signal is presented in Figure 10.

Below are some characteristics of the receiver signals as obtained by these two methods. The results are summarized in Table 1.

Efficiency: In both configurations, for a source voltage of 7.1 V rms the receiver registered a peak voltage of 0.7 mV rms. This gives an efficiency level of -80 dB which is reasonably close to the estimated value at 95 KHz from Experiment I. The relationship between source and receiver voltage was linear up to at least 50 V rms; our driving system was incapable of handling higher voltages at these frequencies.

Directivity: As expected, the receiver in the second configuration was more directive than its counterpart. The half power bandwidth of the array in the second configuration was 17 kHz whereas for the one in the first it was 23 kHz.

Signal to noise ratio: The S/N ratio was practically the same for both configurations: 50 V/V or 34 db for a source voltage of 7.1 V rms. The noise level remained unchanged for higher driving voltages. This equality of noise levels between the two configurations was unanticipated since the second configuration, because of its higher directivity, was expected to be more discriminant than the first towards randomly incident noise.

Rise time: It is in this attribute that configurations 1 and 2 differ most significantly. It takes the signal of configuration 2 six cycles to reach its maximum level, whereas that of configuration 1 achieves it in five cycles. On a time scale, these values correspond to 63 and 52 micro seconds respectively. Also, the curvature of the envelope is different; configuration 2 is exponential looking while configuration 1 is almost linear. There is a very simple reason for these results. Since the wavefront of the plane acoustic pulse (traveling at an angle) impinges on alternating elements exactly one cycle's worth of time apart, the signal obtained by connecting these elements in parallel is a time history of these multiple impacts. For this reason, the pulse corresponding to the array in the second configuration is composed of more cycles than the original source signal and its ends are smoothed out.

Detectability of leading pulse edge: For a source voltage of 7.1 V rms the amplitude of the leading peak was 0.1 mV, which was 5 times greater than the noise level. The amplitude of this peak increased linearly with the source voltage while the noise level, of course, remained constant.

Signal consistency: The fluctuations in time and magnitude of consecutive pulses was measured by "blowing up" the peak corresponding to the leading cycle and recording its variability. The leading peak was found to be consistent within a window of 1 micro seconds and 10 micro volts.

Free waves in pipe wall: As shown in Fig. 7, the receiving array in configuration 1 detects the arrival of pipe wall vibratory

pulse. Its arrival precedes that of the acoustic pulse by 0.47 msec, occurring approximately halfway between excitation of the source array and the arrival of the acoustic pulse. Its magnitude was 0.06 mV; it was 3 times greater than the noise level. Because of its higher directivity, the array in configuration 2 registers a much weaker vibration signal; it is barely above the noise level and can be safely neglected.

CONCLUSIONS

The overall results of this experimental study seem to confirm the feasibility of an externally mounted non resonant flow meter. Signal levels are sufficiently high: the efficiency and S/N levels were higher than expected and the characteristics of the leading pulse edge seem to be acceptable.

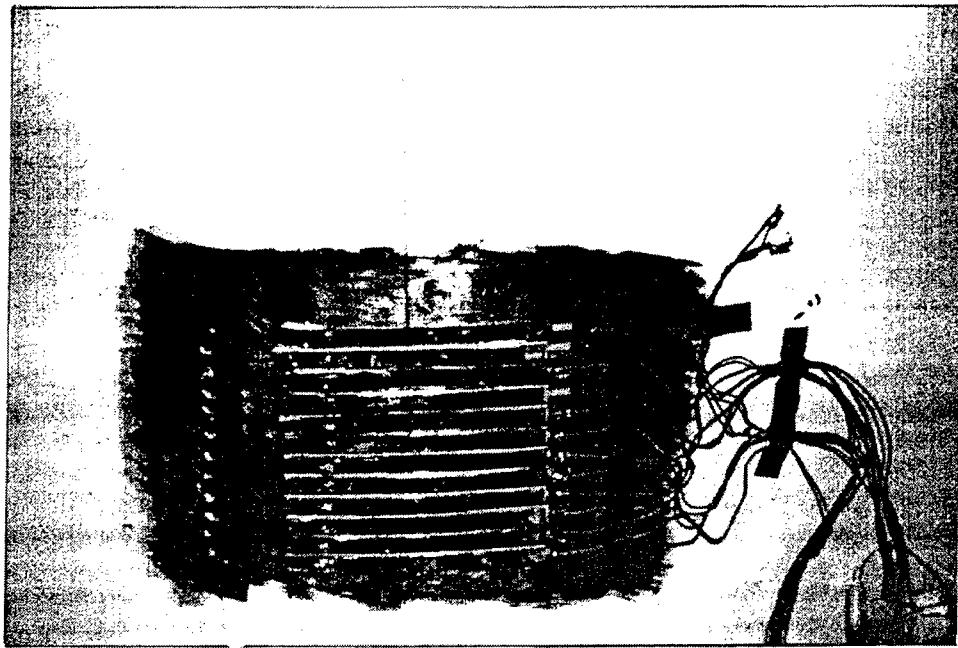
If operation at higher frequencies and lower grazing angles is required, however, a significant reduction in the efficiency levels is to be anticipated. Figure 5 can be used to estimate efficiency levels for frequencies above 100 kHz and even beyond 150 kHz. The close correspondence between the efficiency results of Experiment I and those of Experiment II suggests that our experimental estimates for system efficiency in Figure 5 are valid.

We believe that the next phase of this study should involve the optimization of array shape, in conjunction with element to element phase and amplitude taper as required, for maximum efficiency and minimum rise time. Clearly, rise time would be decreased greatly with no loss of receiver directivity if wavefronts of incoming acoustic pulses were parallel to the surface of the receiving array. Then, all of the elements of the receiving array would be excited simultaneously by the acoustic pulse. Modest improvements in rise time may be achieved by including phase taper in the source arrays that were utilized in this phase of the study. Upon request, we would be happy to prepare a proposal for future work in these or other areas.

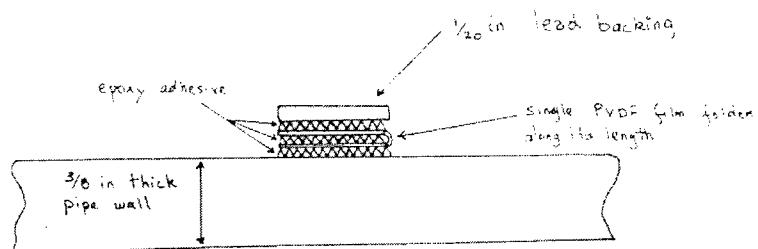


Figure 1: General experimental setup.

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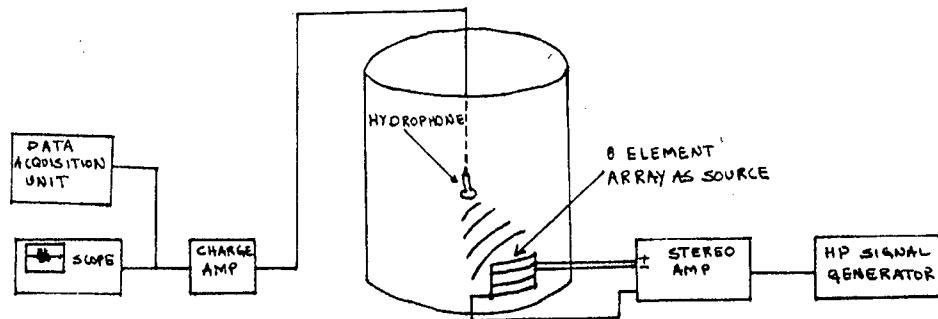


a) Photo of source array.

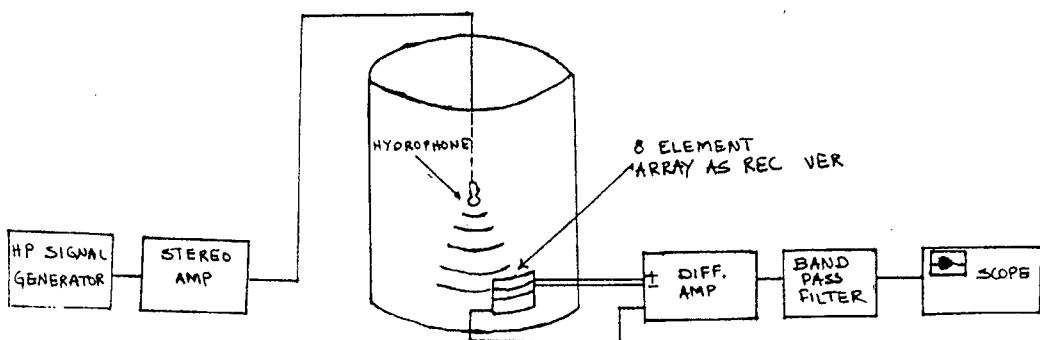


b) Mounting of elements on tank wall. For the source array, conductive epoxy was used between the element and the tank wall as well as between the lead backing and the element. In addition, the tank, together with all the components electrically connected to it, were grounded.

Figure 2: Source array.



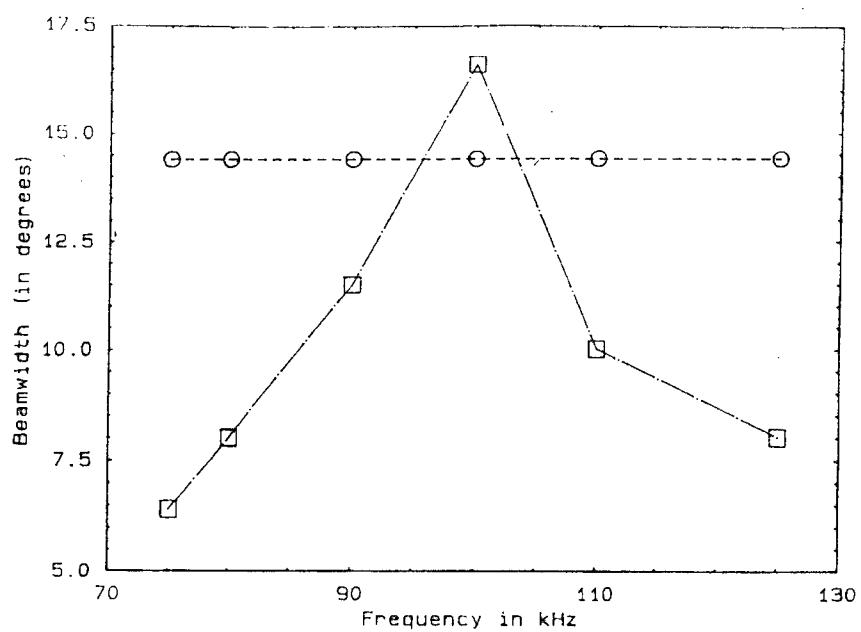
a) Reciprocal experiment A.



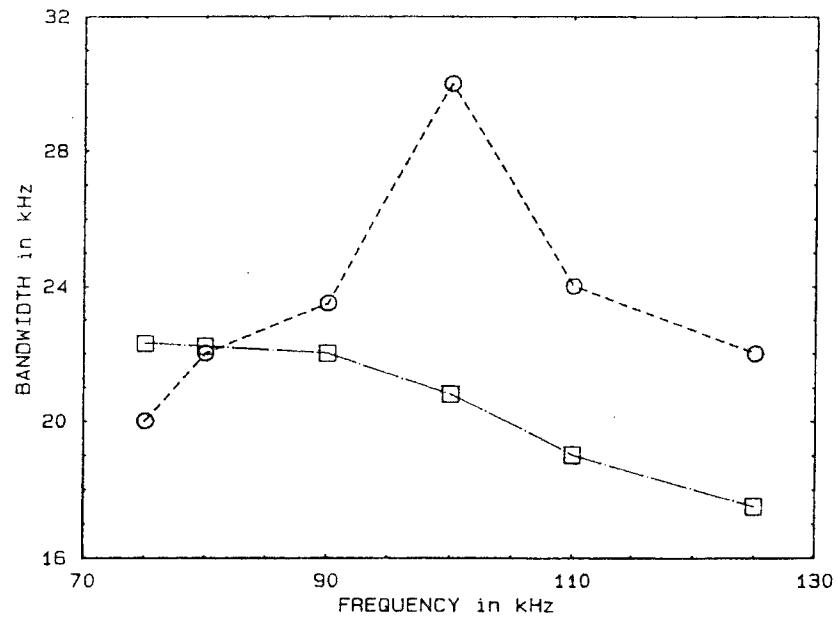
b) Reciprocal experiment B.

Figure 3: Experimental setup for Experiment I.

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a) Half power beamwidth of main lobe.



b) Half power bandwidth.

Figure 4: Directivity of source array.

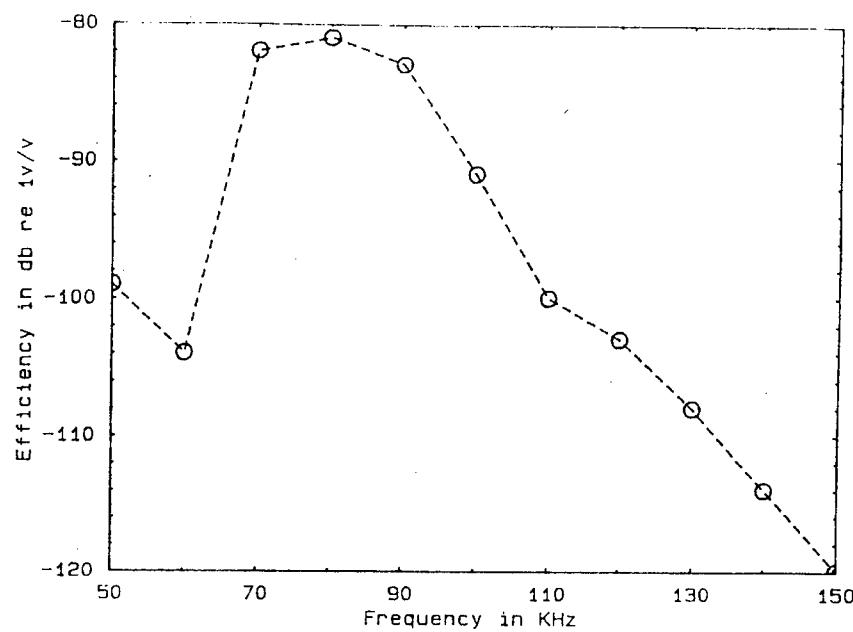


Figure 5: Efficiency vs Frequency obtained through reciprocal experiments of Figure 3ab.

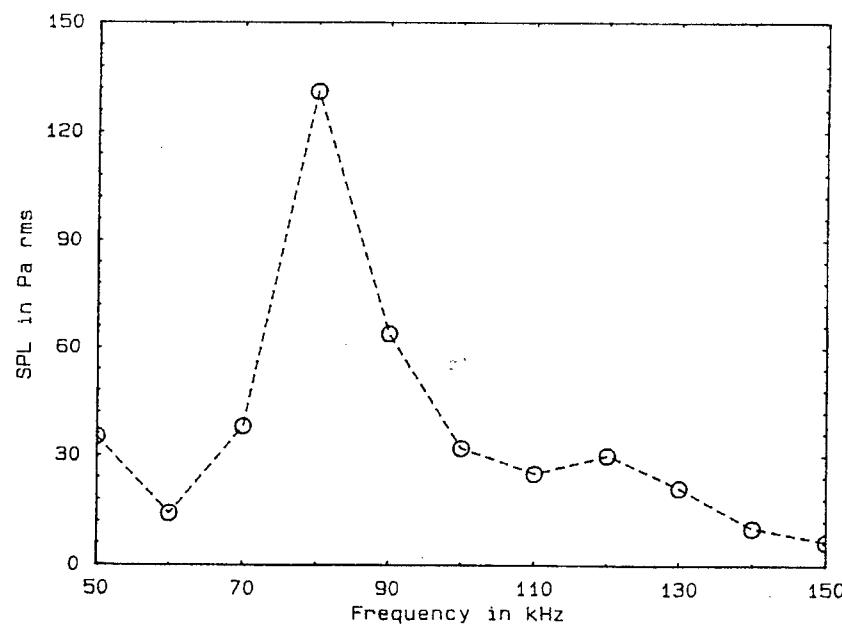
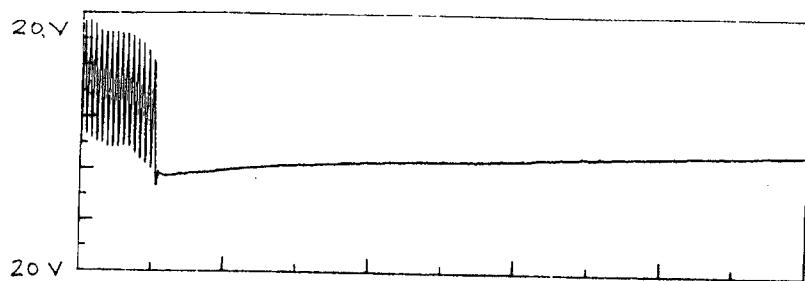
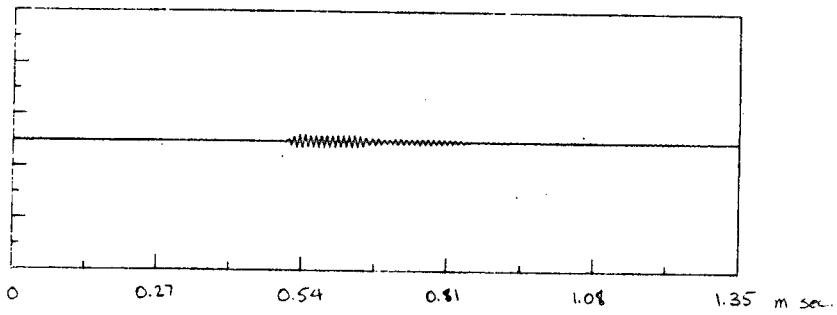


Figure 6: Sound pressure levels in main radiation lobe.

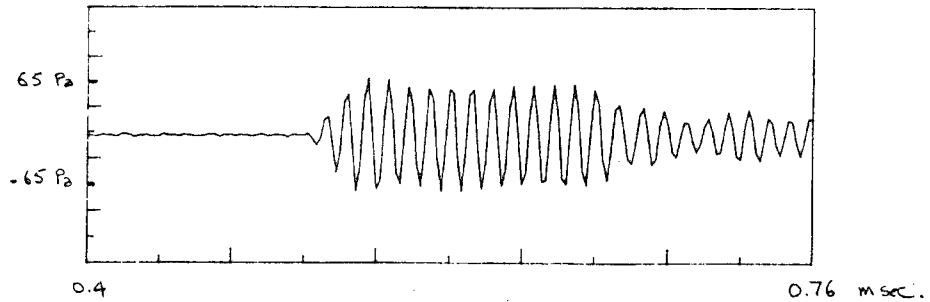
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a) Signal fed into source array. Driving frequency: 96 kHz.



b) Typical time domain response of hydrophone.
Sampling frequency: 0.5 MHz.



c) Blow up of b).

Figure 7

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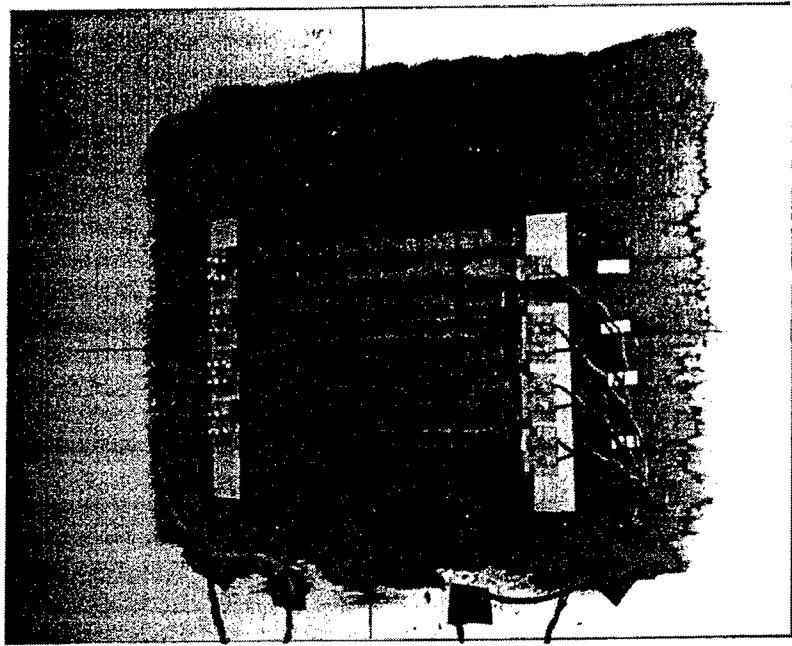
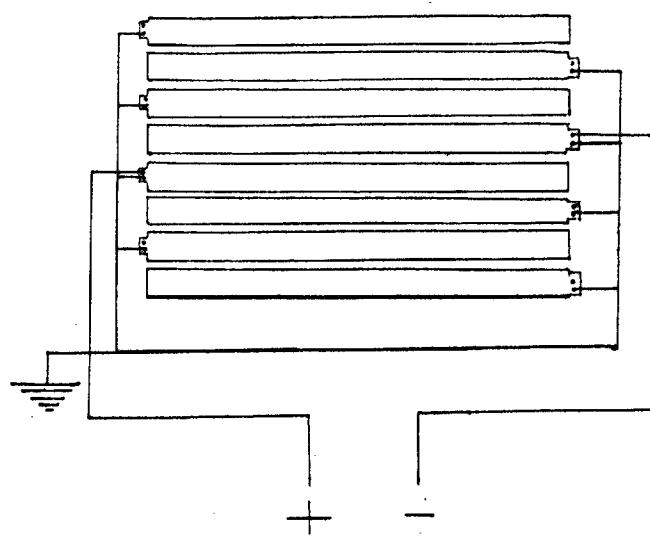
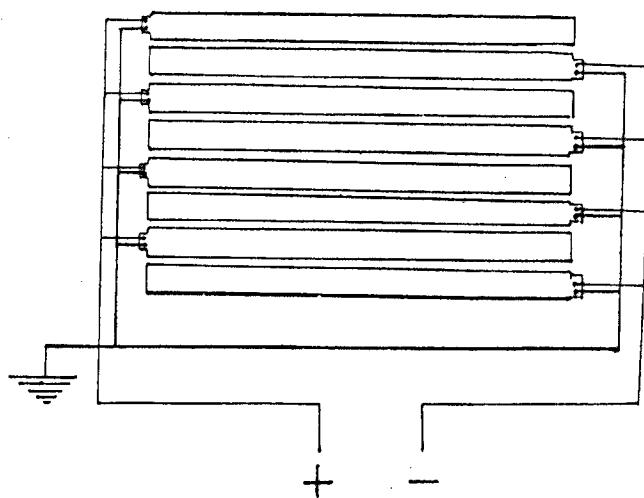


Figure 8: Receiver array as mounted on tank.

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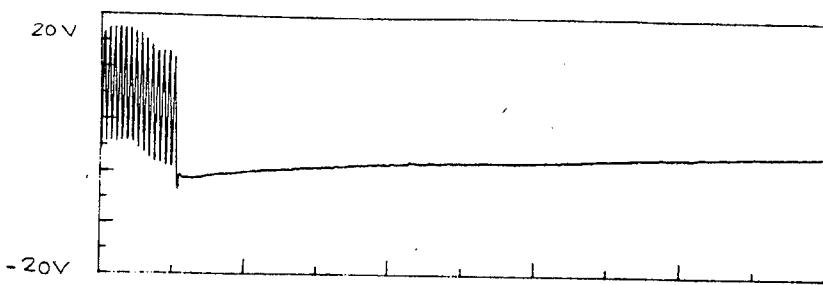
a) Configuration 1.



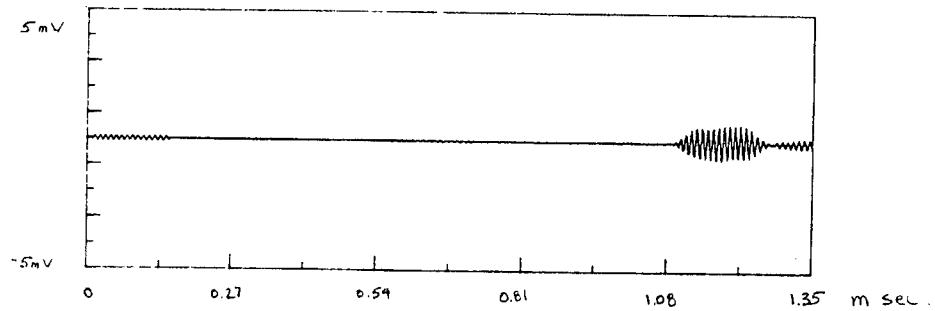
b) Configuration 2.

Figure 9: Receiver array.

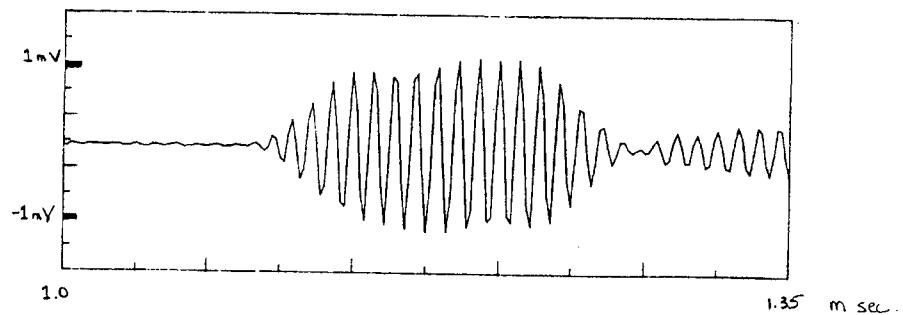
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a) Signal fed into source array at 96 kHz.



b) Typical time domain response of receiver array in configuration 1 (Sampling rate: 0.5 MHz). Notice detection of free structural waves.



c) Blow up of b).

Figure 10

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SUMMARY OF RESULTS FOR EXPERIMENT II

	<u>Configuration 1</u>	<u>Configuration 2</u>
Efficiency at 95 KHz	-80 db	-80 db
Directivity (half power bandwidth)	23 KHz	17 KHz
Signal to noise ratio	34 db	34 db
Rise time	52 micro sec.	63 micro sec.
Amplitude of leading cycle (7.1 V rms at source)	0.1 mV	0.1 mV
Signal consistency windows	1 micro sec. 10 micro V	1 micro sec. 10 micro V
Free wave amplitude	0.06 mV	0.02 mV

TABLE 1.

Appendix D:
Report Dated 27 May 1994
From R. H. Lyon Corporation
Further Results of Sensitivity
Analysis of Transducer
Performance

MEMORANDUM

To: F.C. Lowell, Jr.; Accusonic
From: Dick Lyon, Leonid Malinin; RH Lyon Corp
Subject: Further Results of Sensitivity Analysis of Transducers Performance
Date: May 27, 1994

Following up on our discussion of the first set of the results, outlined in our memo of May 18, 1994, we proceeded with further modeling. The following issues were addressed: a) comparison with the obtained experimental data (0.045" thickness backing, 90° diametrical path), and b) analysis of the profile of the surface (Transducer velocity) vs. (frequency, backing's thickness). The latter is intended to provide an easy visual estimation of the expected performance of the transducers. As earlier, the velocity is obtained on the inner surface of the load (facing the epoxy, not the fluid).

The model included one layer of PVDF. The thickness of the load was changed from 3/8" to 0.395". Other parameters are shown on the plots. The angles shown on the plots are incidence angles (= 90° - grazing angle).

1. Results for a thicker backing.

The results for the 0.045" thickness of the backing (1.143 mm) and 0.02 mm epoxy are shown in figs. 1 (single 104 μ layer), 2 (single 52 μ layer). Most of the peaks on the plots are split, with the left summit being the lumped and the right summit the plate resonances. The thicker backing (larger mass) shifts the lumped resonance towards the lower frequencies. The backing's thickness was varying from 0.045" to 0.0225" (0.57 to 1.14 mm). The corresponding range of variation of the resonant frequency is smaller than for the thinner backing (see the previous memo); the thinner plate just moves the lumped resonance closer to the plate one. (When crossing, they suppress each other). Figs. 3,4 show the influence of the large grazing angles (the diametrical path). The wave speed along the surface of the load becomes infinity in this case, and the load behaves as a mass (fig.3.). The remaining peak is due to the lumped resonance. The additional notch (due to the plate impedance) appears at the plot when the grazing angle is 75° (fig.4.).

2. Transducer velocity maps. The following plots cover the practical range of parameters and can serve as a guidance as to in what direction to tune up the system. We modeled the system with one 52 μ layer, the load thickness being .395". The plots are organized as follows.

Grazing angle→	45°			30°		
	Losses			Losses		
Insulation Thickness, mm ↓	.02	.05	.1	.02	.05	.1
.1	Fig.5	Fig.6	Fig.7	Fig.11	Fig.12	Fig.13
.2	Fig.8	Fig.9	Fig.10	Fig.14	Fig.15	Fig.16

Shown on the plots are contour lines of the velocity (on the load's inner surface, see above), i.e., the lines where the value of velocity is constant. The lines are drawn in the space of parameters, which are frequency and lead backing thickness. The labels are in logarithmic scale, e.g., -5 means that velocity along this line is 10^{-5} meter/sec per volt. The crosses on the plots (they may be slightly off-set from the lines) point at the lines in question. Just for illustration, figs. 17, 18 show a 3D plot and a conventional velocity vs. frequency plot, corresponding to fig. 8. The plots allow, within the accuracy of the considered model, to specify the parameters (thickness of the backing and epoxy, frequency, etc.), ensuring the required velocity amplitude.

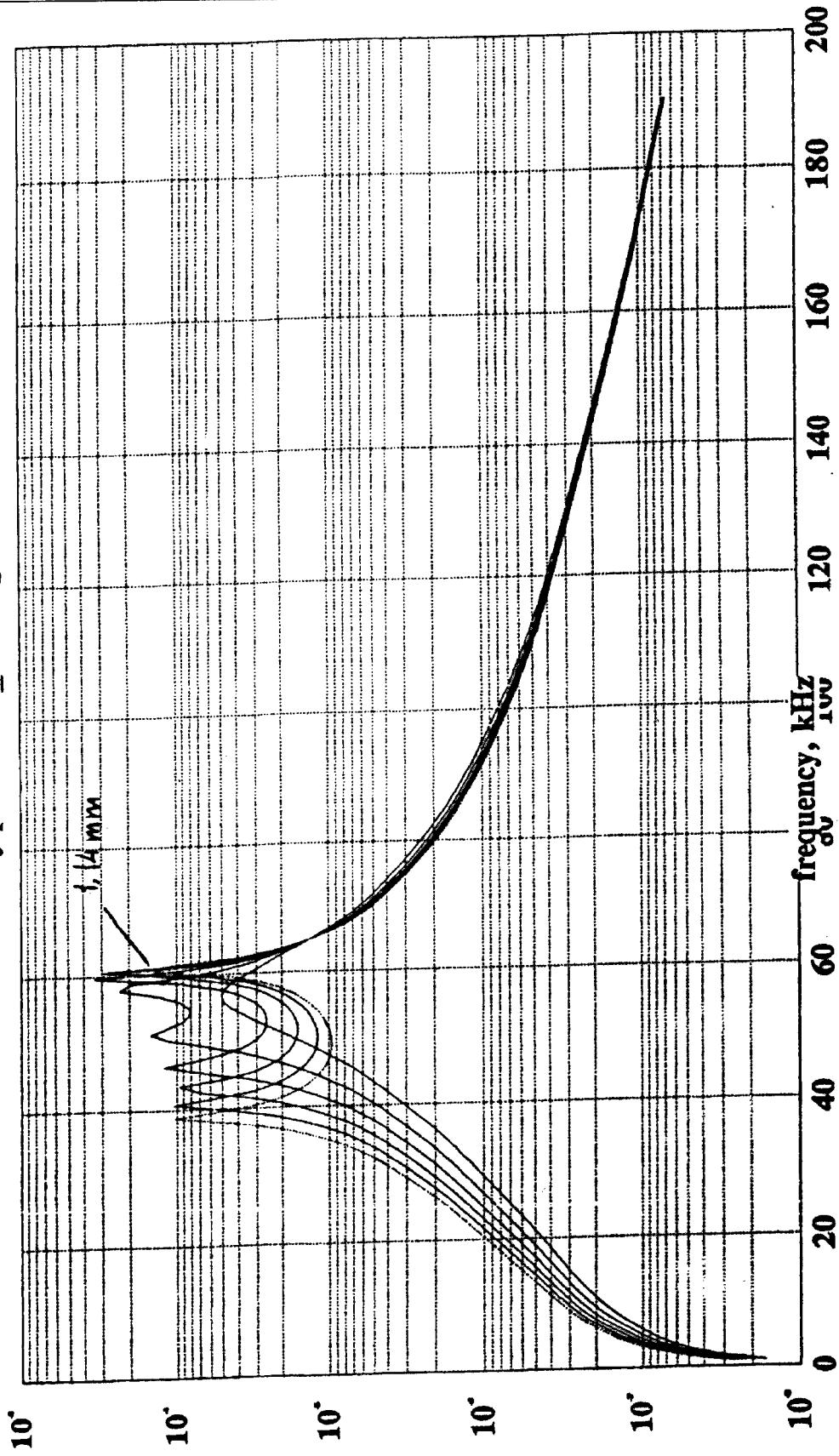
The topography of the contour lines can be described as follows. First, there is a ridge at ≈ 40 kHz (for 45° angle) and at ≈ 65 kHz (for 30° angle), passing parallel to the abscissa axis (backing's thickness), that is, almost independent on this parameter (as well as on damping). This ridge is related to the plate resonance. Then, there is a second ridge, going South-East from the frequency axis. This one corresponds to the lumped resonance, and its location and amplitudes depend on the thicknesses and damping. Though a finer mesh (41 points along the abscissa axis) was specified for these plots, the individual peaks still can be distinguished on the second ridge at the 0.02 damping. They are an artifact owing to a limited resolution, and will coalesce with further refining of the mesh, as happens at higher damping.

Comparing the plots, one can separate the set of parameters which are "more tolerant" with respect to the 100 kHz resonance, i.e., which provide a broader peak in the space of parameters. E.g., considering the effect of epoxy thickness h_{ins} , we compare figs. 5 and 8. For the thinner (0.1 mm) epoxy the width of the ridge at 100 kHz at the -4.75 level is about four times more than for 0.2 mm thickness. The same applies to figs. 11, 14 (compare the width at -5.5 level). The wider ridge means that the system maintains the indicated amplitudes in the wider range of the argument (backing thickness). The thicker (softer) epoxy requires, naturally, a thinner (lighter) backing (the tuned up backing thickness h_b changes from ≈ 0.125 mm, fig. 8, to ≈ 0.24 mm, fig. 5). The epoxy bulk module E_{ins} has the inverse effect (only the ratio E_{ins}/h_{ins} matters).

The grazing angle, as we mentioned above, changes the wave speed along the surface of the load. Its effect is reduced primarily to the shift in the position of the plate-related resonance. It can be seen that the 45° angle provides higher amplitudes at 100 kHz - perhaps, because the plate resonance is closer.

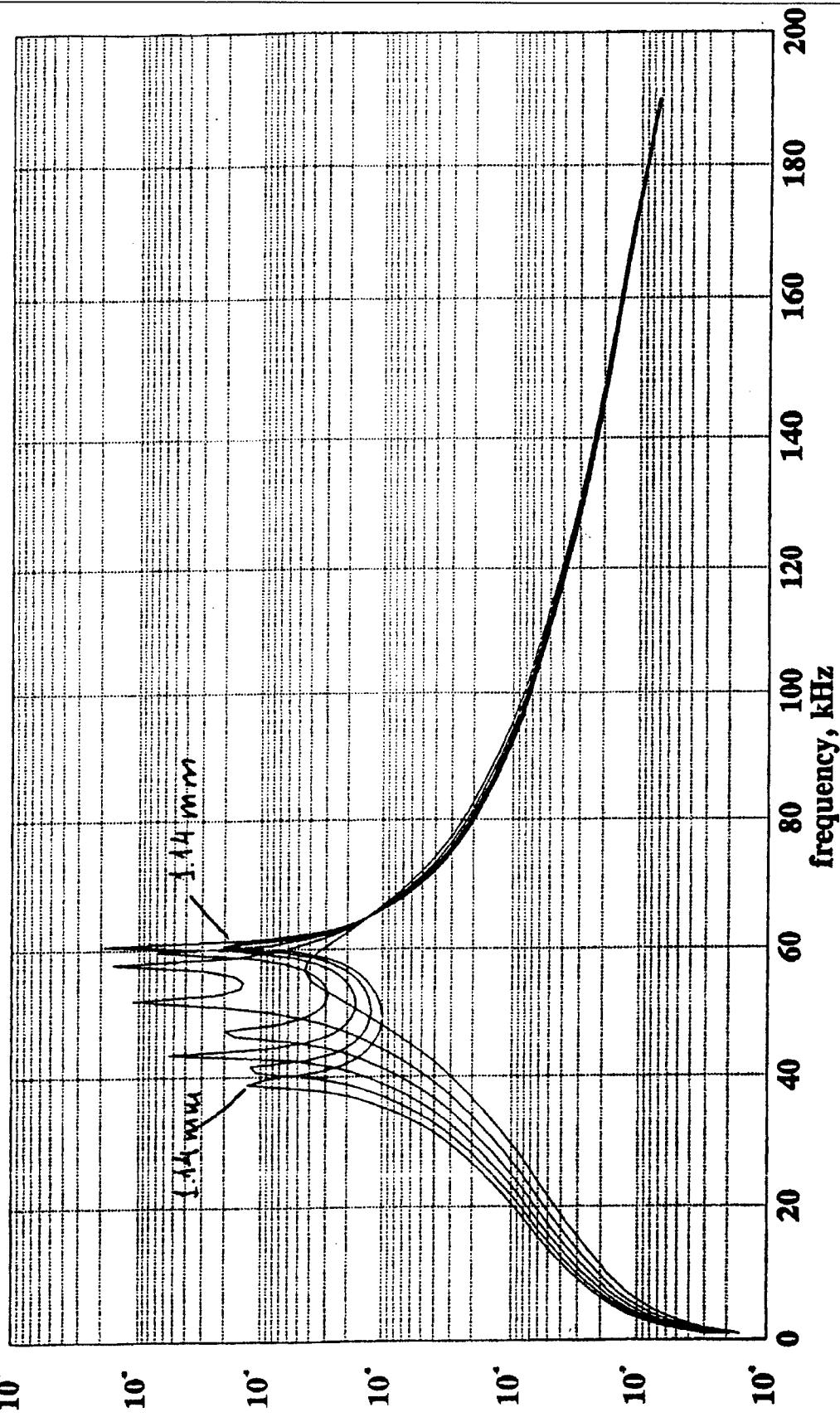
3. Directions of further studies. The current model can be applied to a) plotting the analogous profiles to estimate the influence of the parameters which are hard to control (e.g., ratio E_{ins}/h_{ins}); b) adjusting the parameters of the system in order to make the lumped ridge possibly close and parallel to the 100 kHz line (to make the tuning less demanding); c) adjusting the parameters to get the required height (amplitudes) of the ridge, and similar tasks.

Fig.1. Transducer velocity per volt. $h_{backing} = 0.57 \dots 1.14$ mm



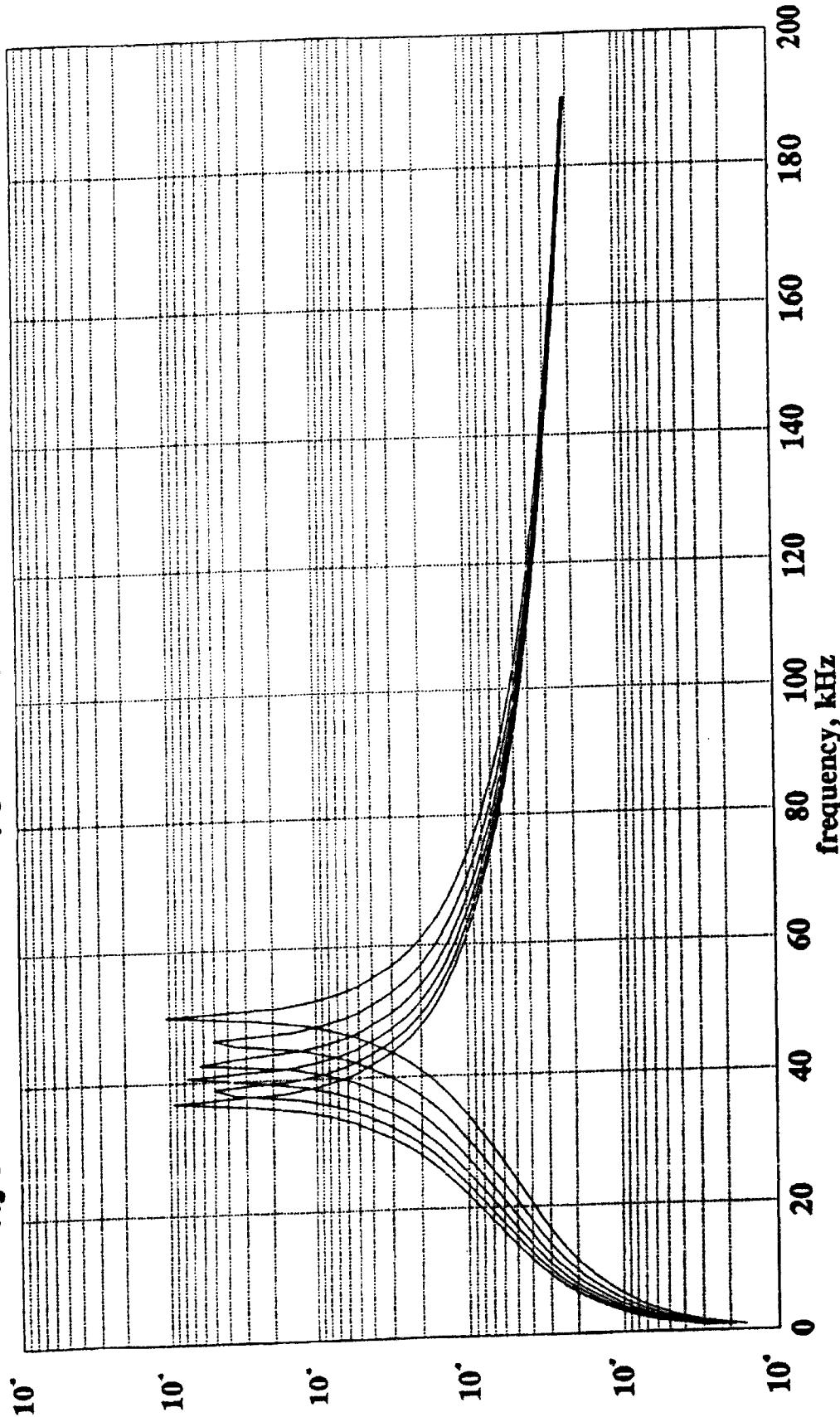
single 104mu/45 degrees, $h_{load} = .395"$, $h_{ins} = .2$ mm, losses = 0.02

Fig.2. Transducer velocity per volt. $h_{backing} = 0.57 \dots 1.14$ mm



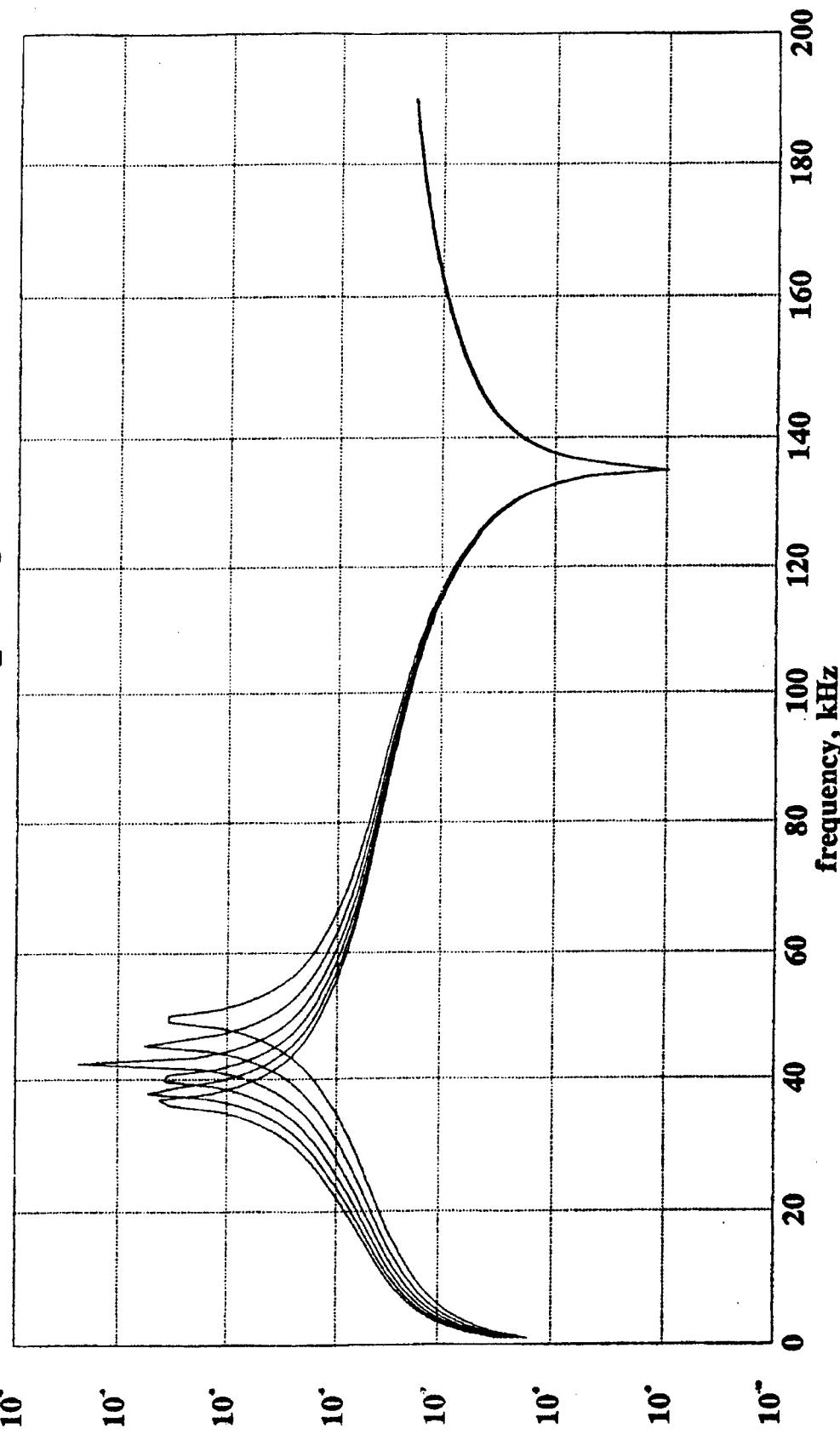
single 52mu/45 degrees, $h_{load} = .395"$, $h_{ins} = .2\text{mm}$, losses=0.0

Fig. 3. Transducer velocity per volt. $h_{backing} = 0.57\ldots 1.14$ mm



single 52μ / 0 degrees, $h_{load} = .395"$, $h_{ins} = .2$ mm, losses = 0.0

Fig.4. Transducer velocity per volt. $h_{backing} = 0.57\dots 1.14$ mm



single 52 μ /15 degrees (incidence), $h_{load} = .395"$, $h_{ins} = .2$ mm, losses = 0.0

Fig.5. Transducer velocity, m/s per volt; Contour lines (labels are log10). 0.1mm epoxy, losses = .02;.395", 40 degre., 1 layer, 344

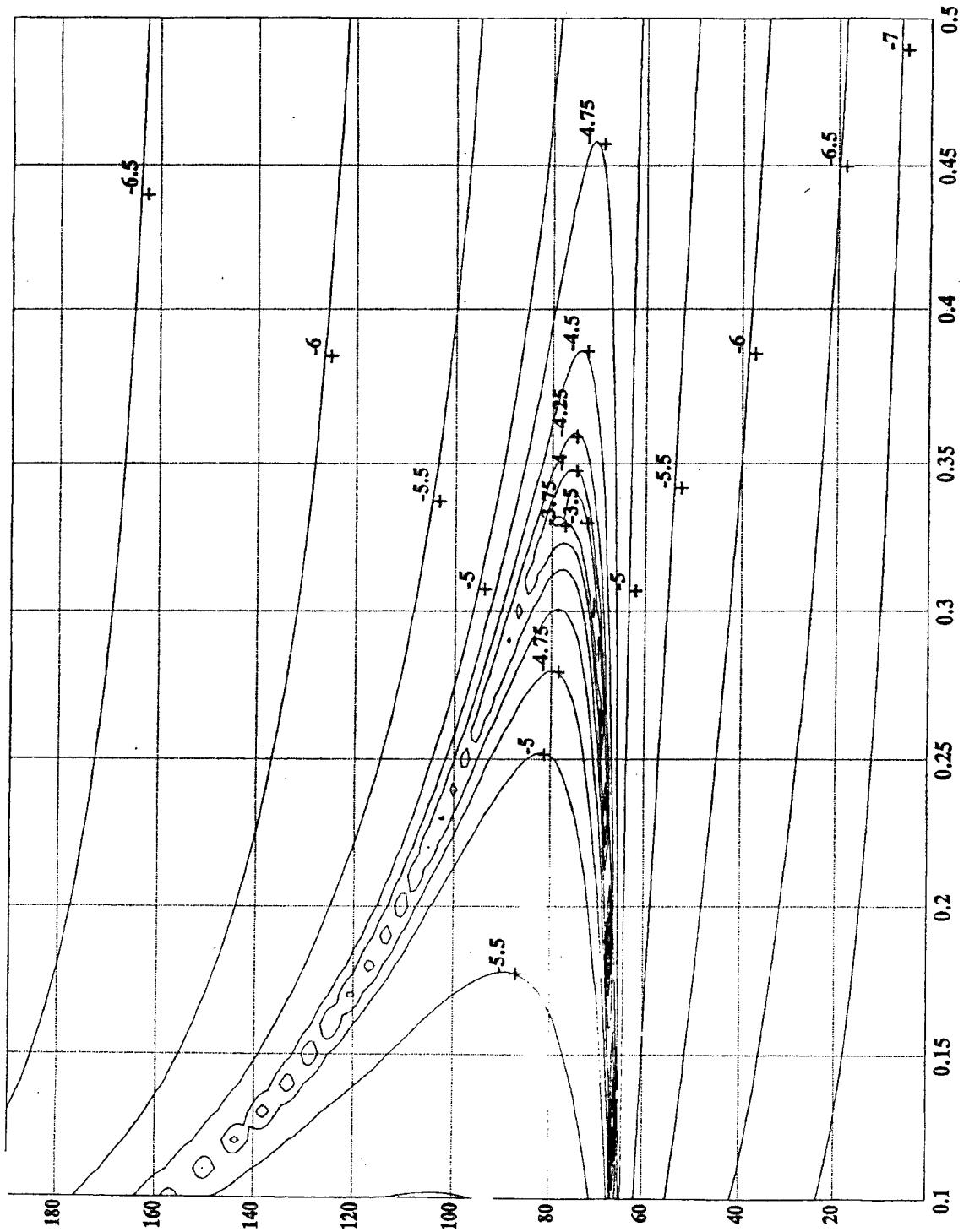
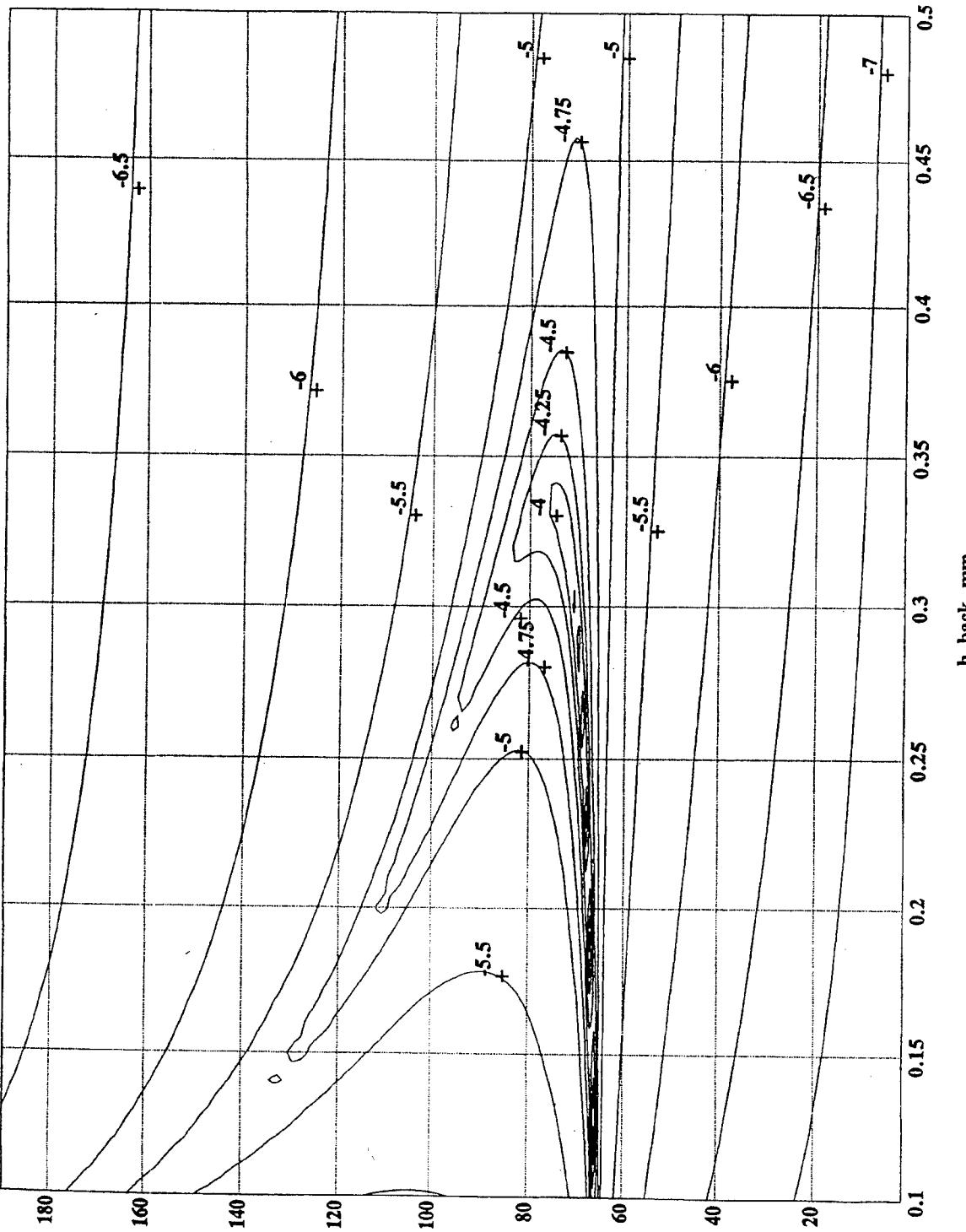
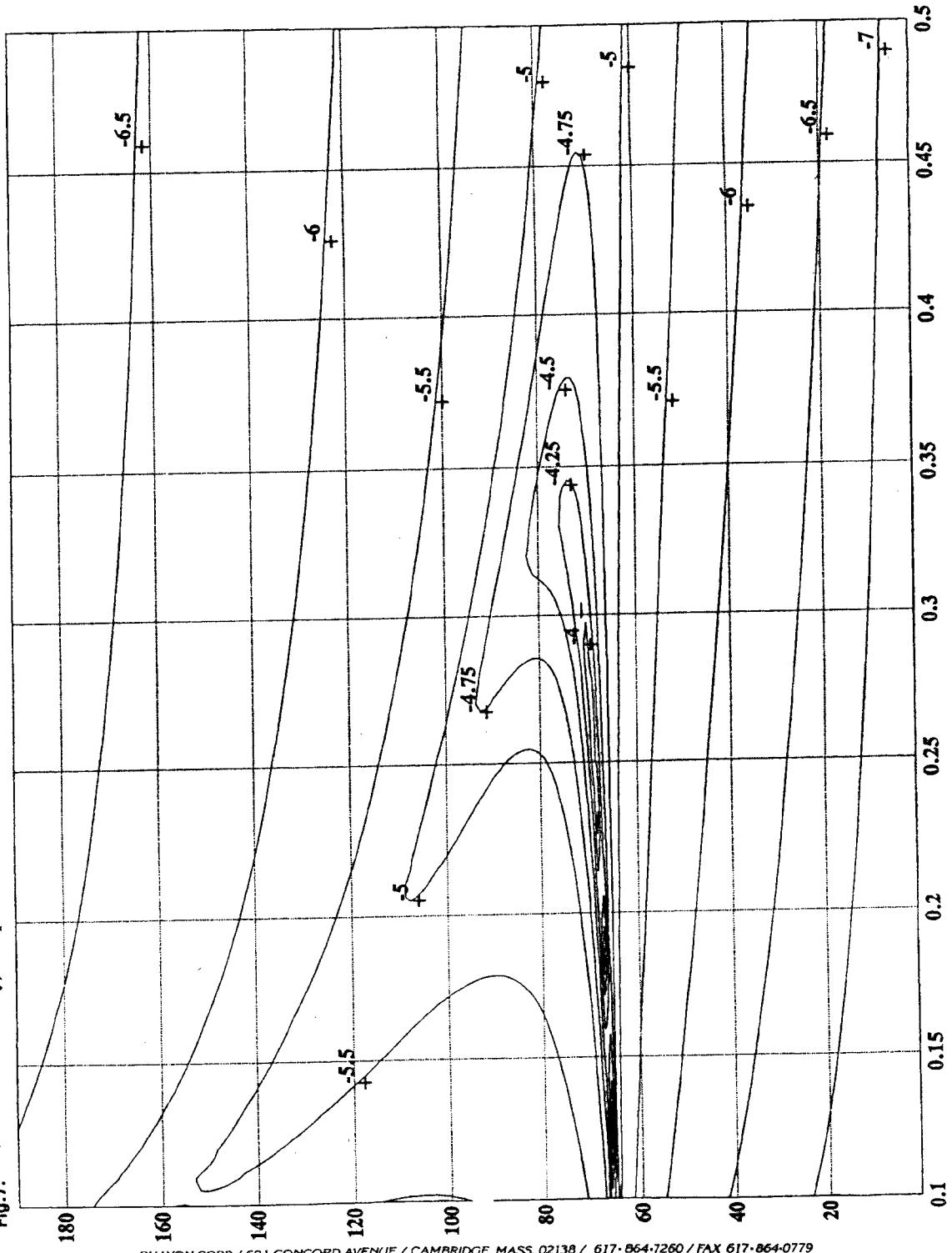


Fig. 6. Transducer velocity, m/s per volt: Contour lines (labels are \log_{10}). 0.1mm epoxy, losses = .025, 395°, 45 degr., 1 layer, 52μ



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Fig.7. Transducer velocity, m/s per volt: Contour lines (Labels are log10). 0.1mm epoxy, losses=.1; 395°, 45 deg., 1 layer, 52μ



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Fig. 8. Transducer velocity, m/s per volt; Contour lines (labels are log10). 0.2mm epoxy, losses = .02; 395°, 45 deg., 1 layer, 52μ

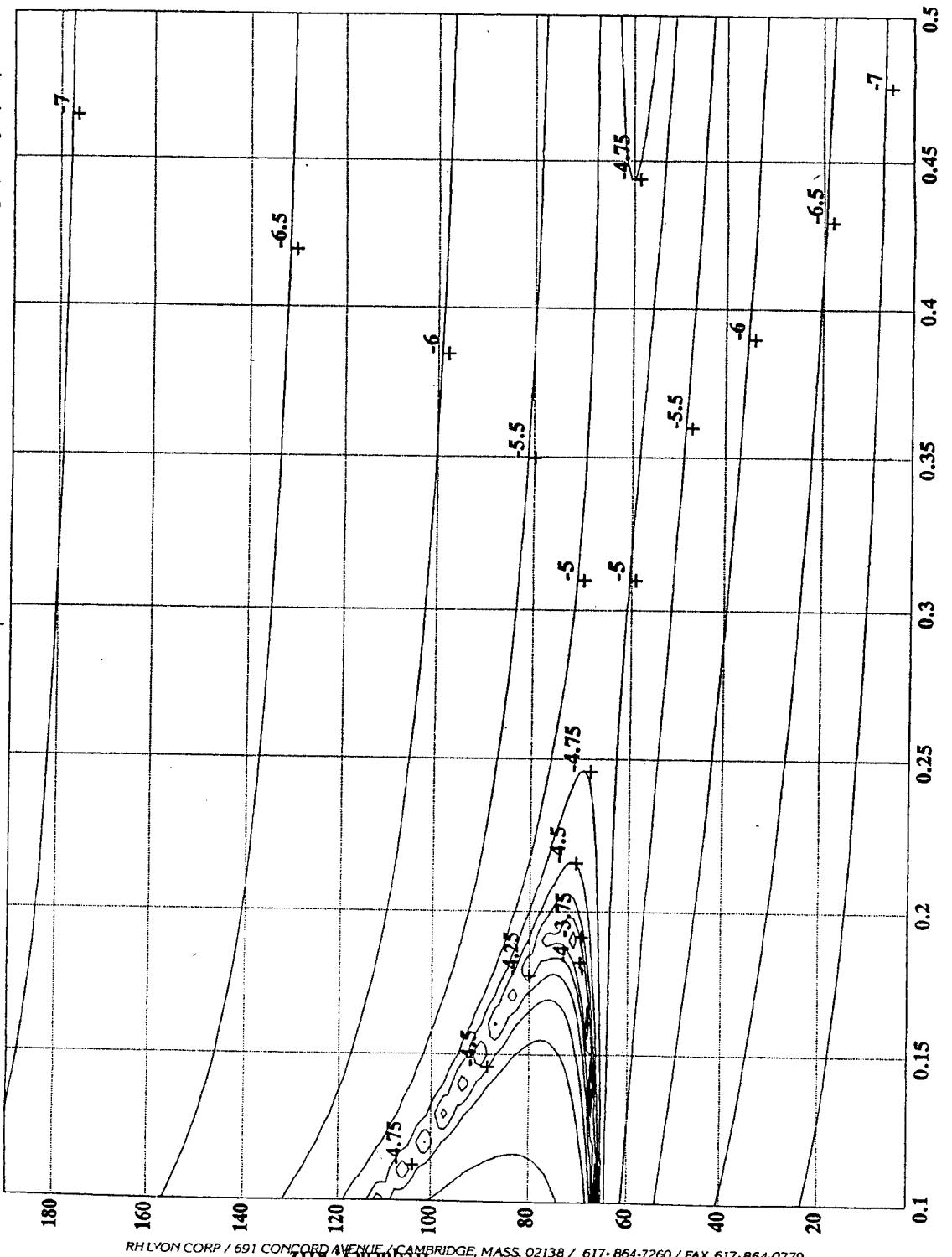
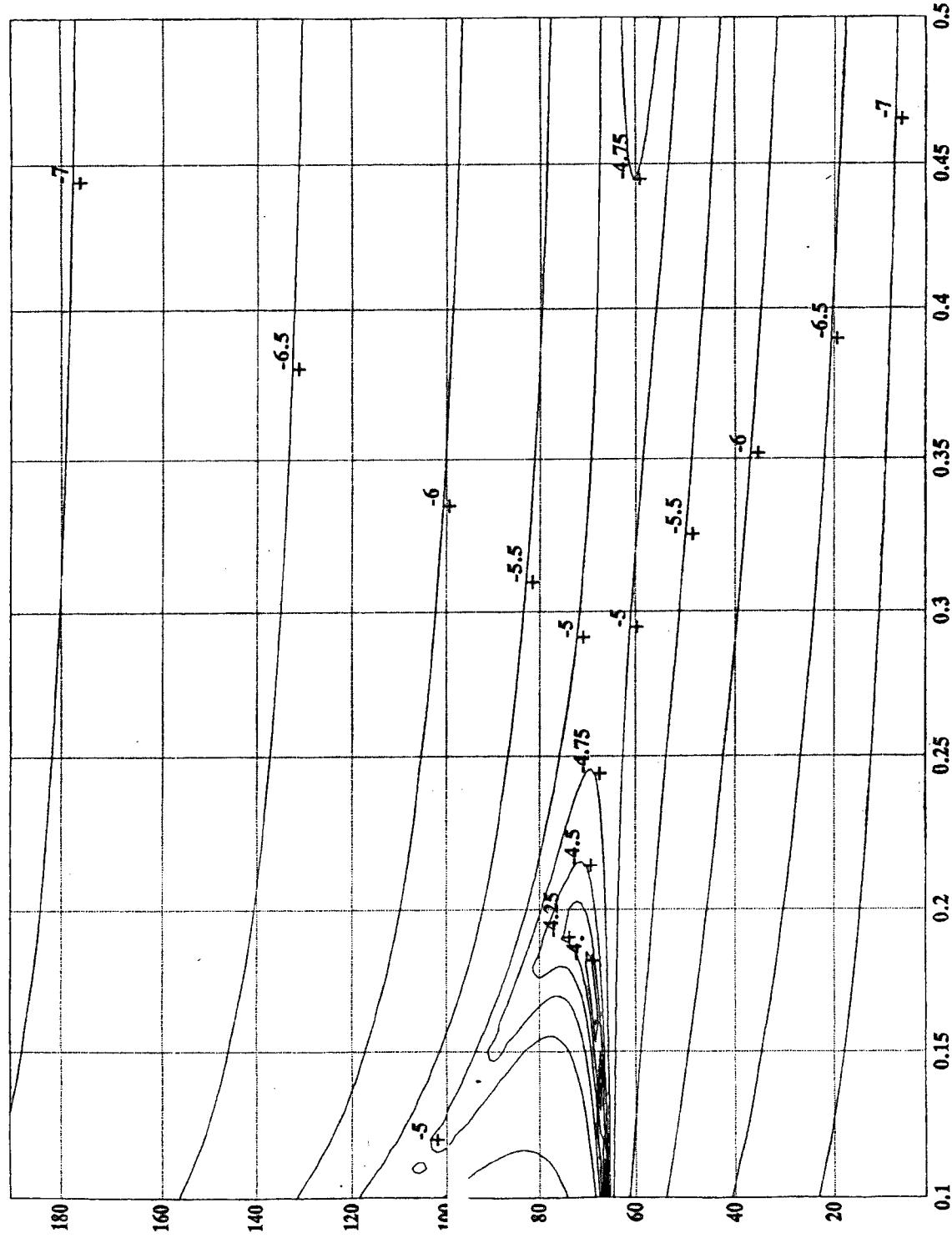
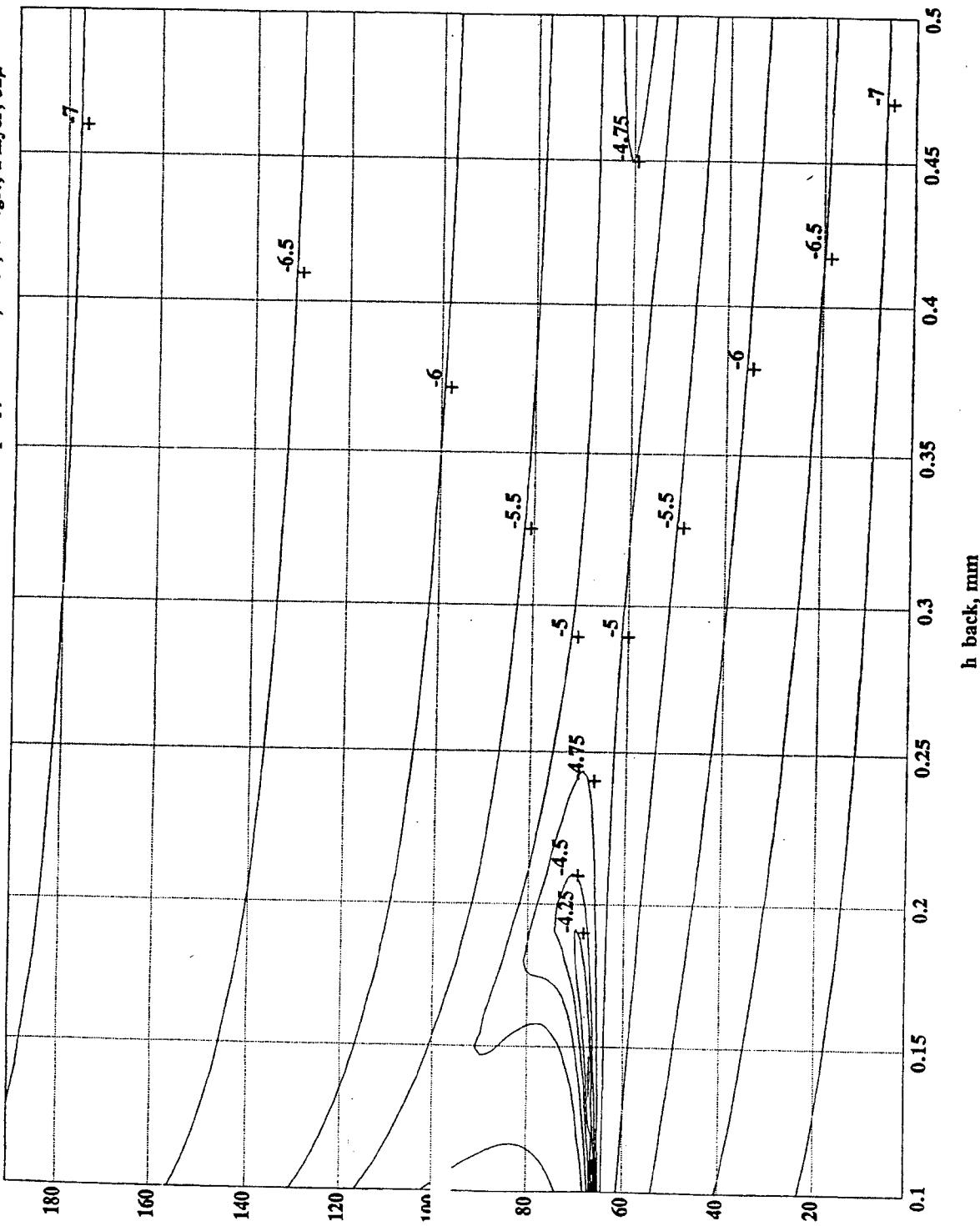


Fig.9. Transducer velocity, m/s per volt; Contour lines (labels are log10). 0.2mm epoxy, losses = .05;.395",45 degr., 1 layer, 52 μ



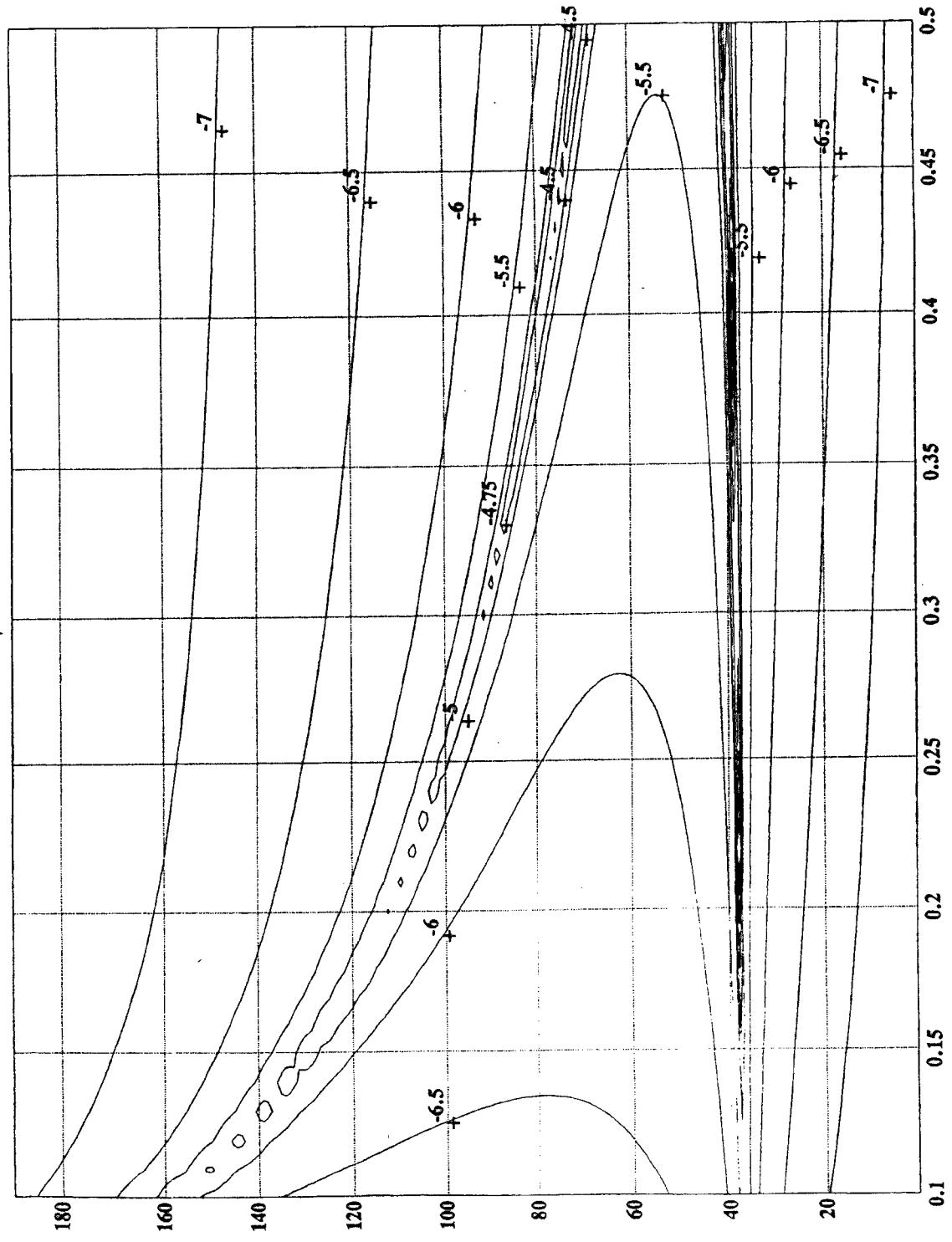
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Fig.10. Transducer velocity, m/s per volt; Contour lines (labels are log10). 0.2mm epoxy, losses = .1; 395°, 45 degr., 1 layer, 52 μ



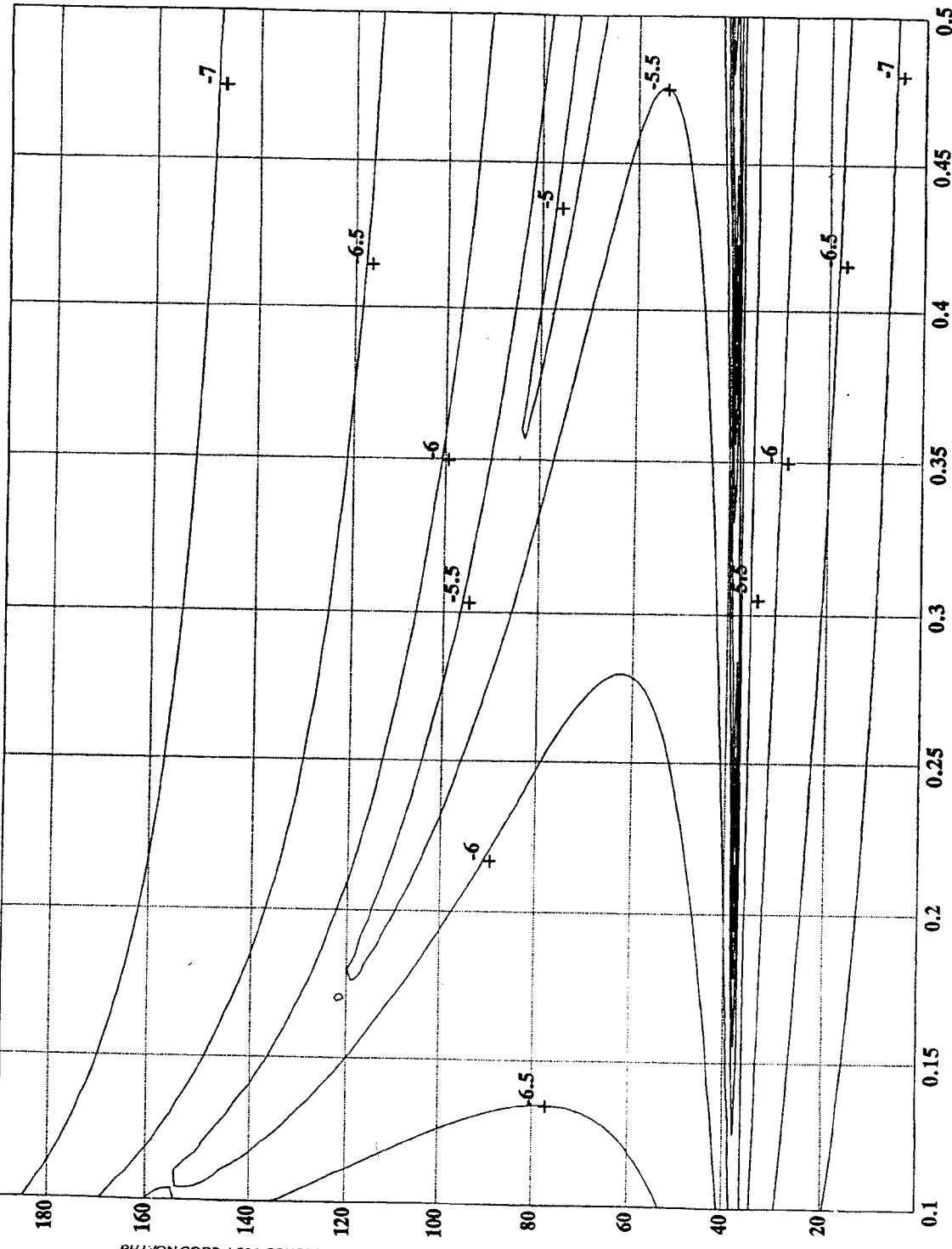
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Fig.11. Transducer velocity, m/s per volt: Contour lines (labels are log10). 0.1mm epoxy, losses = .02; .395°, 60 deg., 1 layer, 52μ



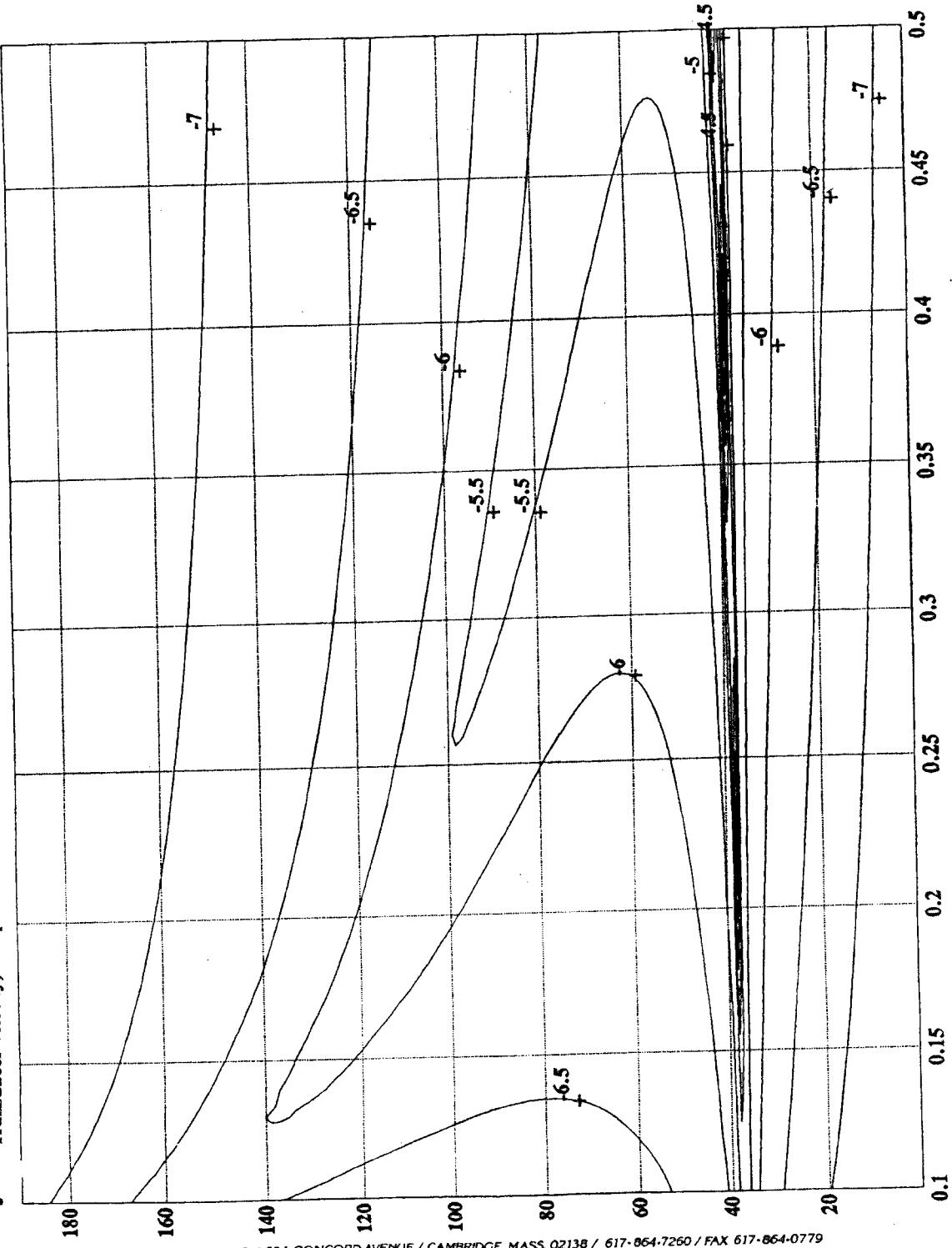
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Fig. 12. Transducer velocity, m/s per volt; Contour lines (labels are log10). 0.1mm epoxy, losses = .05; 395", 60 degr., 1 layer, 52 μ



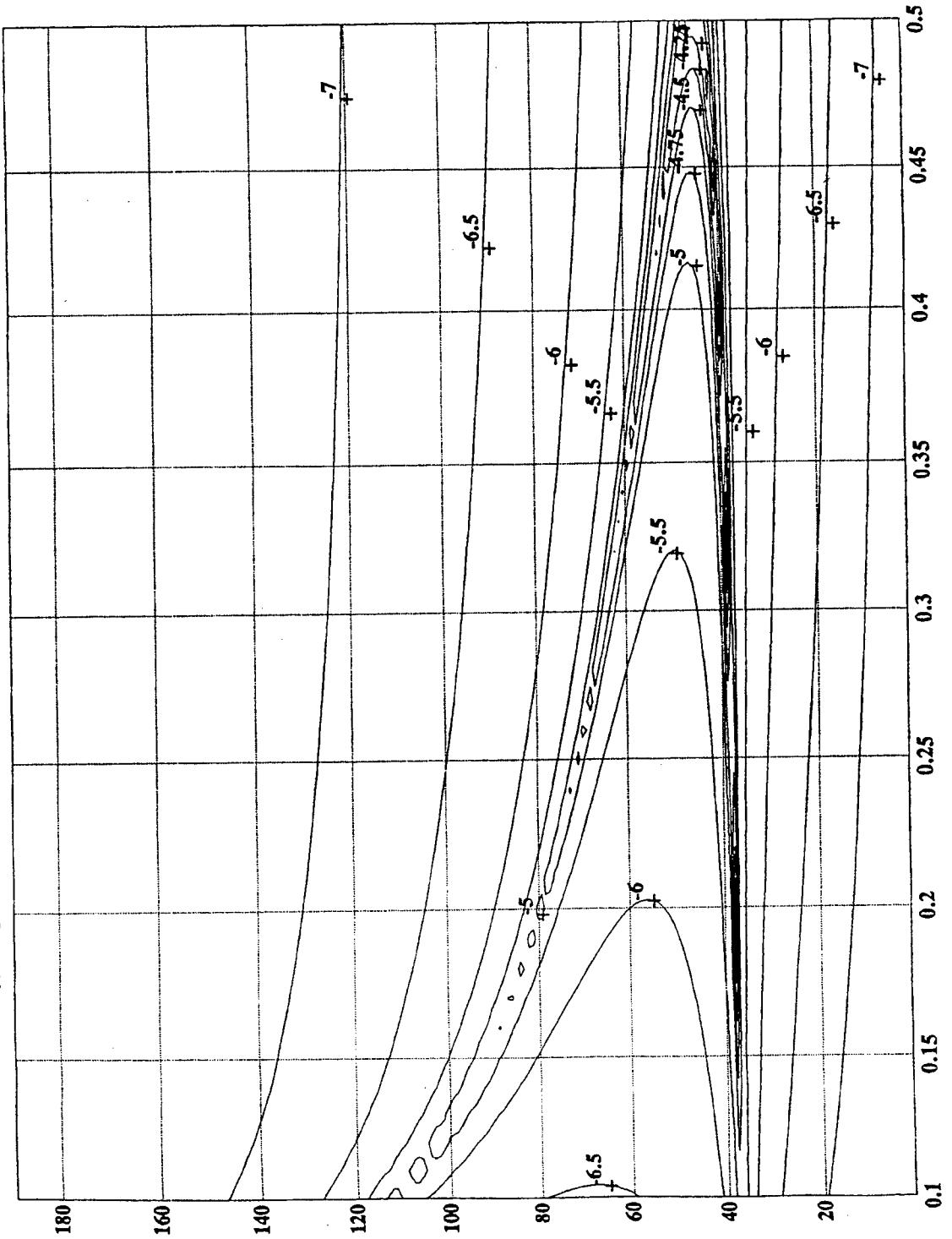
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Fig.13. Transducer velocity, m/s per volt: Contour lines (Labels are log10). 0.1mm epoxy, losses=.1;395",60 degr., 1 layer, 52 μ



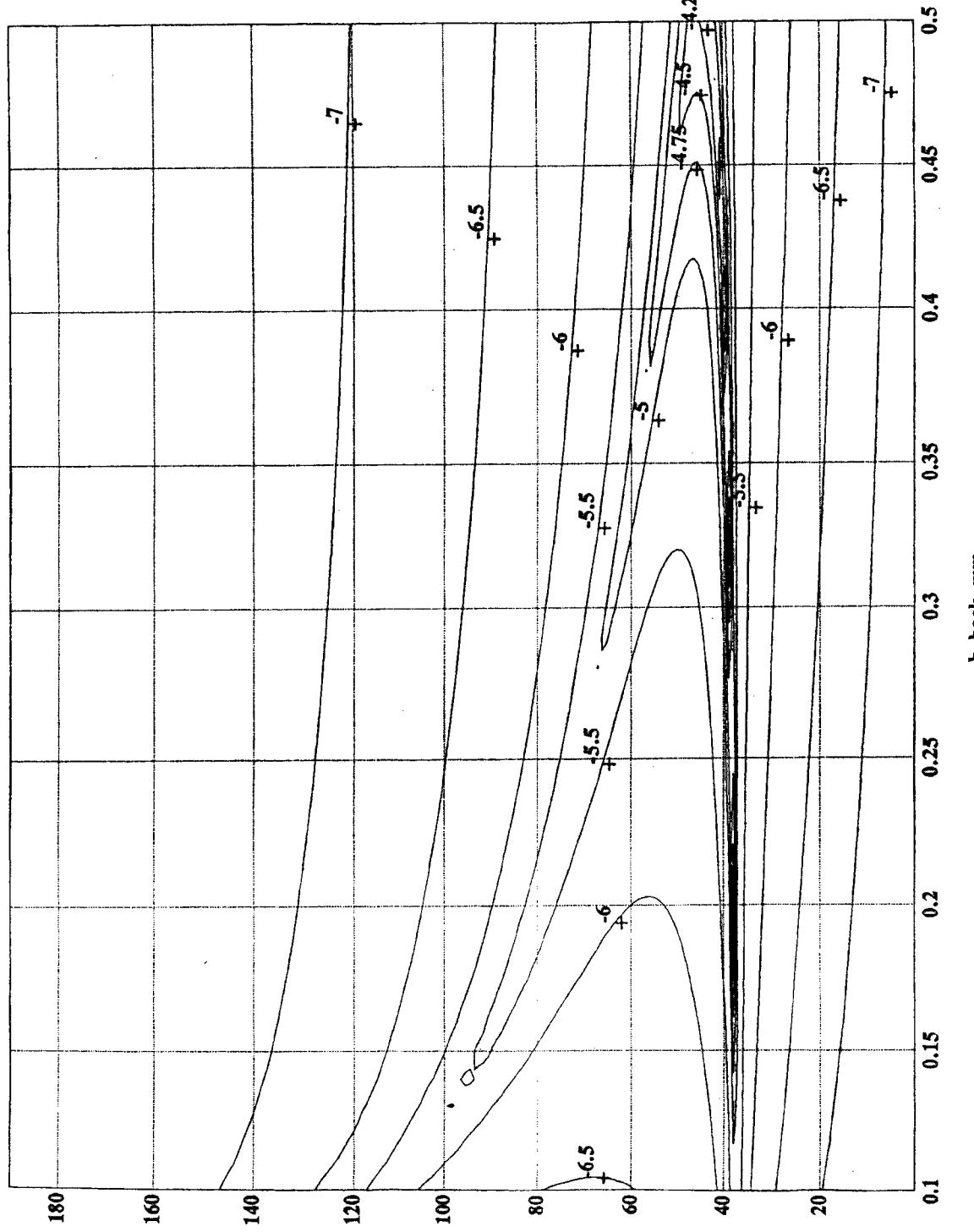
RH LYON CORP / 691 CONCORD AVENUE / CAMBRIDGE, MASS. 02138 / 617-864-7260 / FAX 617-864-0779

Fig.14. Transducer velocity, m/s per volt: Contour lines (labels are log10). 0.2mm epoxy, losses = .02; 395°, 60 deg., 1 layer, 52μ



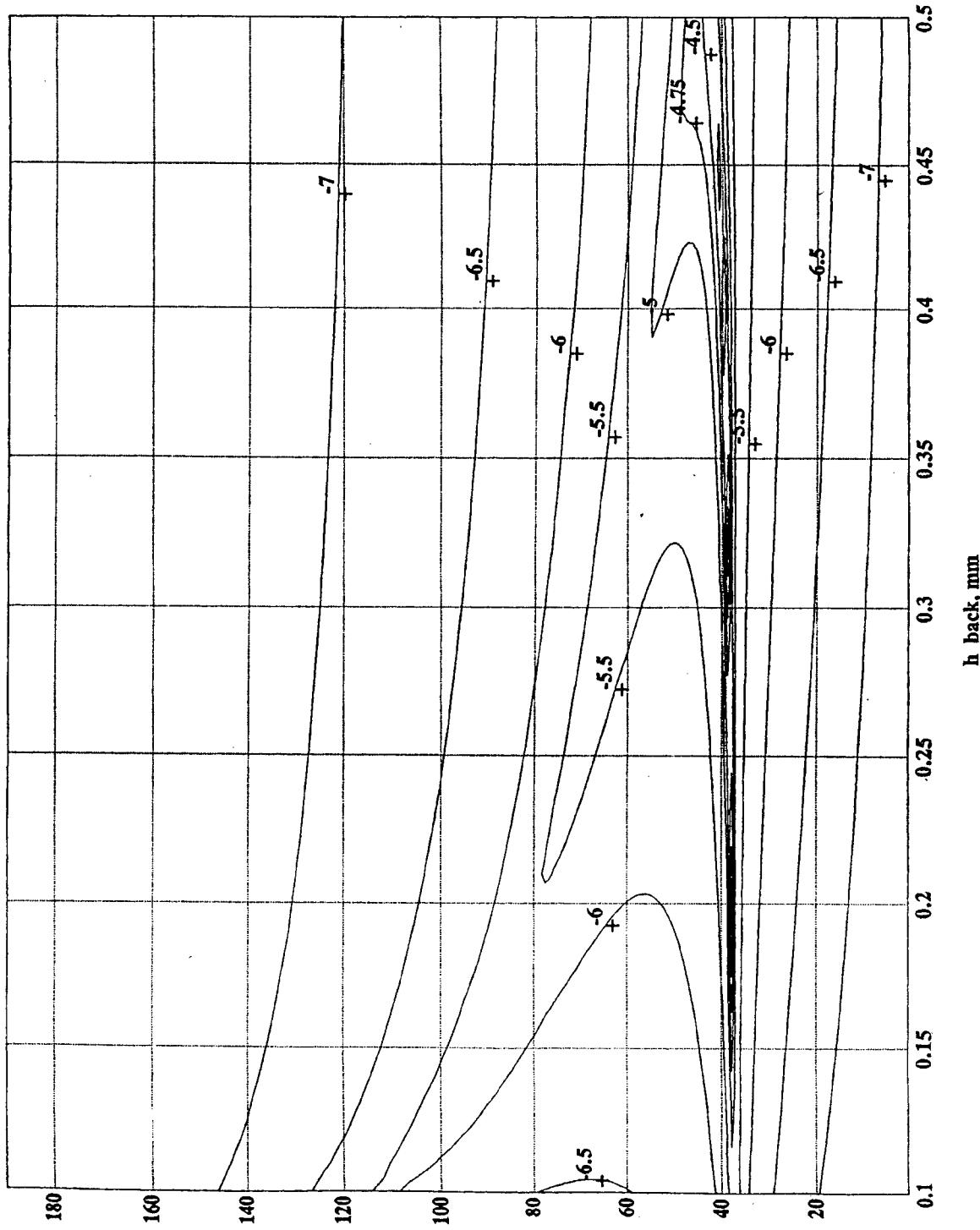
RH LYON CORP / 691 CONCORD AVENUE / CAMBRIDGE, MASS. 02138 / 617-864-7260 / FAX 617-864-0779

Fig.15. Transducer velocity, m/s per volt: Contour lines (labels are log10). 0.2mm epoxy, losses=.05; .395", 60 degr., 1 layer, 52μ



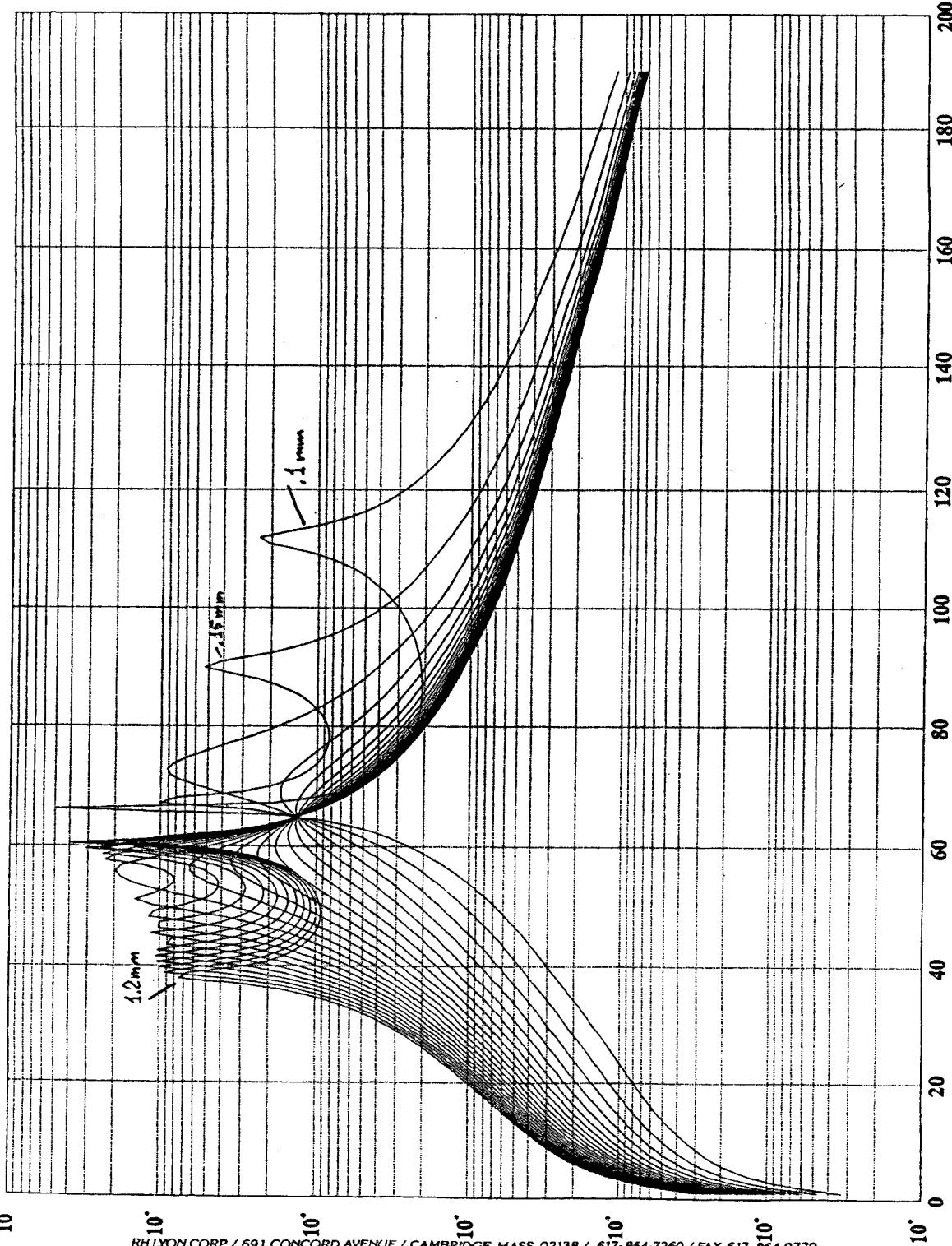
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Fig. 16. Transducer velocity, m/s per volt: Contour lines (labels are log10). 0.2mm epoxy, losses=.1; 395°, 60 deg., 1 layer, 52 μ

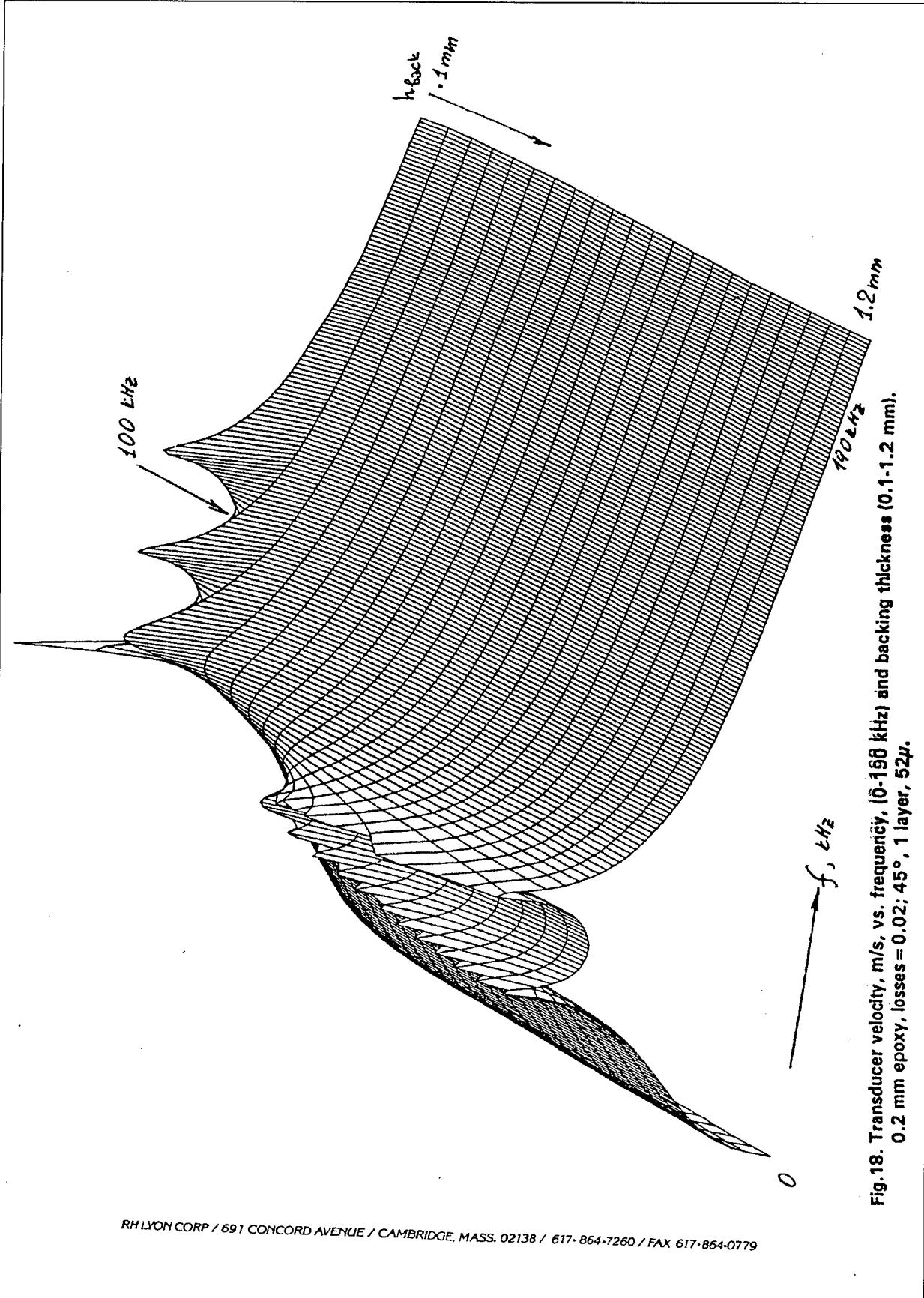


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Fig. 1 / Transducer velocity, m/s, vs. frequency, Hz.
0.2 mm epoxy, losses = 0.02; 45°, 1 layer, 52μ .



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MEMORANDUM

To: F.C. Lowell, Jr.; Accusonic
From: Dick Lyon, Leonid Malinin; RH Lyon Corp
Subject: Results of Sensitivity Analysis of Transducers Performance
Date: May 18, 1994

The results of the analysis for a two-layer transducer are presented. The values of parameters needed to tune up the assembly at 100 kHz are indicated.

1. Input data. Transducer components and an electrical equivalent circuit were sketched in our fax of April 11. The following values of parameters were accepted for the current model:

PVDF:

$E = 2250 \text{ MPa}$ (Bulk modulus);

$\rho = 1780 \text{ kg/m}^3$ (density);

$h = 104 \mu\text{m}$ (thickness);

$d_{33} = 33 \cdot 10^{-12} \text{ (m/Volt)}$;

Load: steel, $h = 3/8"$;

Backing: lead ($\rho = 11340 \text{ kg/m}^3$), $h = 0.15 \dots 0.45 \text{ mm} = 0.0059 \dots 0.0177"$;

Epoxy:

$E = 240 \text{ MPa}$ (quoted by Tra-Con for epoxy 2902);

$h = 0.05 \dots 0.1 \text{ mm} = 0.00197 \dots 0.003937"$;

losses = 0 ... 0.1 (dimensionless);

Fluid: water ($c = 1465 \text{ m/s}$).

Angle of incidence: $30^\circ, 45^\circ, 60^\circ$ (grazing angle $60^\circ, 45^\circ, 30^\circ$).

The data indicated in your fax of 05/13 thus far have not been introduced. The layer of insulation ($h = 7.5 \cdot 10^{-4} \text{ "} = 19.05 \mu\text{m}$, $E = 450 \text{ psi} = 3100 \text{ MPa}$) is much stiffer per unit area than the surrounding PVDF and epoxy and is represented by a negligible compliance in the equivalent circuit.

2. Tuning up. A typical plot (velocity at the load per volt vs. frequency) is presented in fig. 1. Different curves correspond to different thickness of the backing. Most of the curves on the plot have two peaks, the first corresponding to the resonance of the infinite plate, the second to the resonance of the lumped parameters' part of the circuit, with the plate acting like a stiffness. The relative positions of the two peaks depend on the parameters of the system. The plate-related resonance, not surprisingly, is not very sensitive to the thickness of the backing. It is the second one that is governed by this parameter. Changing the backing thickness around .3mm (for the given set of the parameters), the resonance can be tuned to 100 kHz. (The spread in the peaks' height is primarily due to resolution).

If the epoxy layer is thicker than .05mm and therefore softer, then, to keep the (lumped

mass)/(lumped stiffness) ratio the same (i.e., tuned to 100 kHz), the mass is to be reduced, as shown in fig. 2. The amplitude of the transducer velocity is also reduced. To keep the response higher, the epoxy should be kept as thin as possible, and the backing's thickness selected appropriately.

3. Variations in parameters. The effect of losses in the insulation and epoxy is illustrated by fig. 3. The plate-related peaks are not affected; the "lumped" ones are. A 10% gain in the losses results in approximately 10 times (20 dB) drop in the velocity at the load.

If a single layer transducer is used, it is equivalent to deleting the correspondent stiffnesses of the PVDF and one layer of the epoxy (effect of the PVDF mass is insignificant). These compliances are connected in series with the others in the circuit; the system becomes stiffer, and more mass is needed to tune it up (see fig. 4). The response amplitude is respectively lower.

The steering angle affects the effective wavelength along the surface of the load. As this angle changes, the plate-related peak moves along the frequency axis, while the "lumped" peak remains relatively stable. In fig. 5 shown are the curves for the 60° incidence angle (the grazing angle is 30°). When the plate-related peak passes through the lumped peak (at a grazing angle close to 63°), they suppress each other.

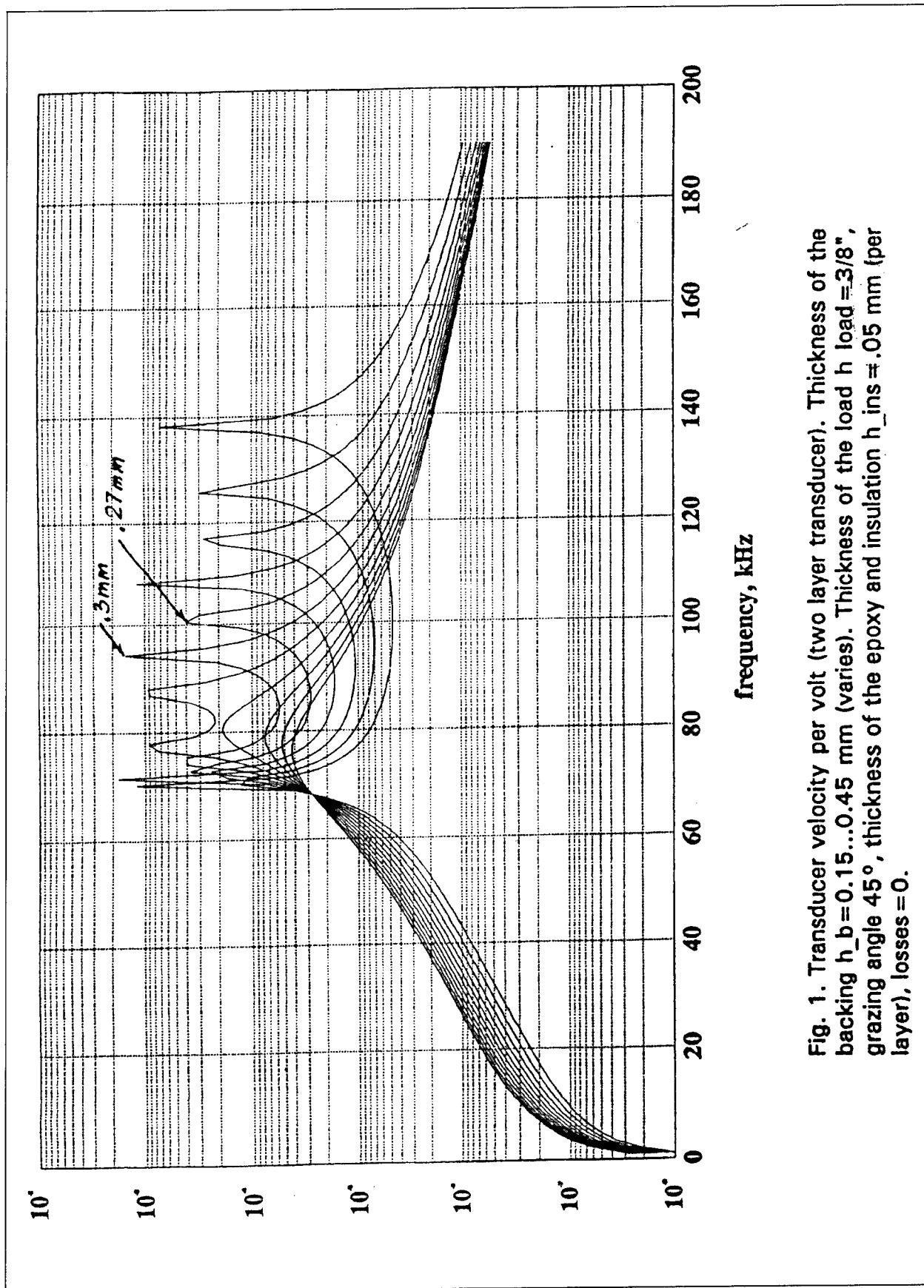


Fig. 1. Transducer velocity per volt (two layer transducer). Thickness of the backing $h_b = 0.15 \dots 0.45$ mm (varies). Thickness of the load h load = $3/8"$, grazing angle 45° , thickness of the epoxy and insulation $h_{ins} \approx 0.05$ mm (per layer), losses = 0.

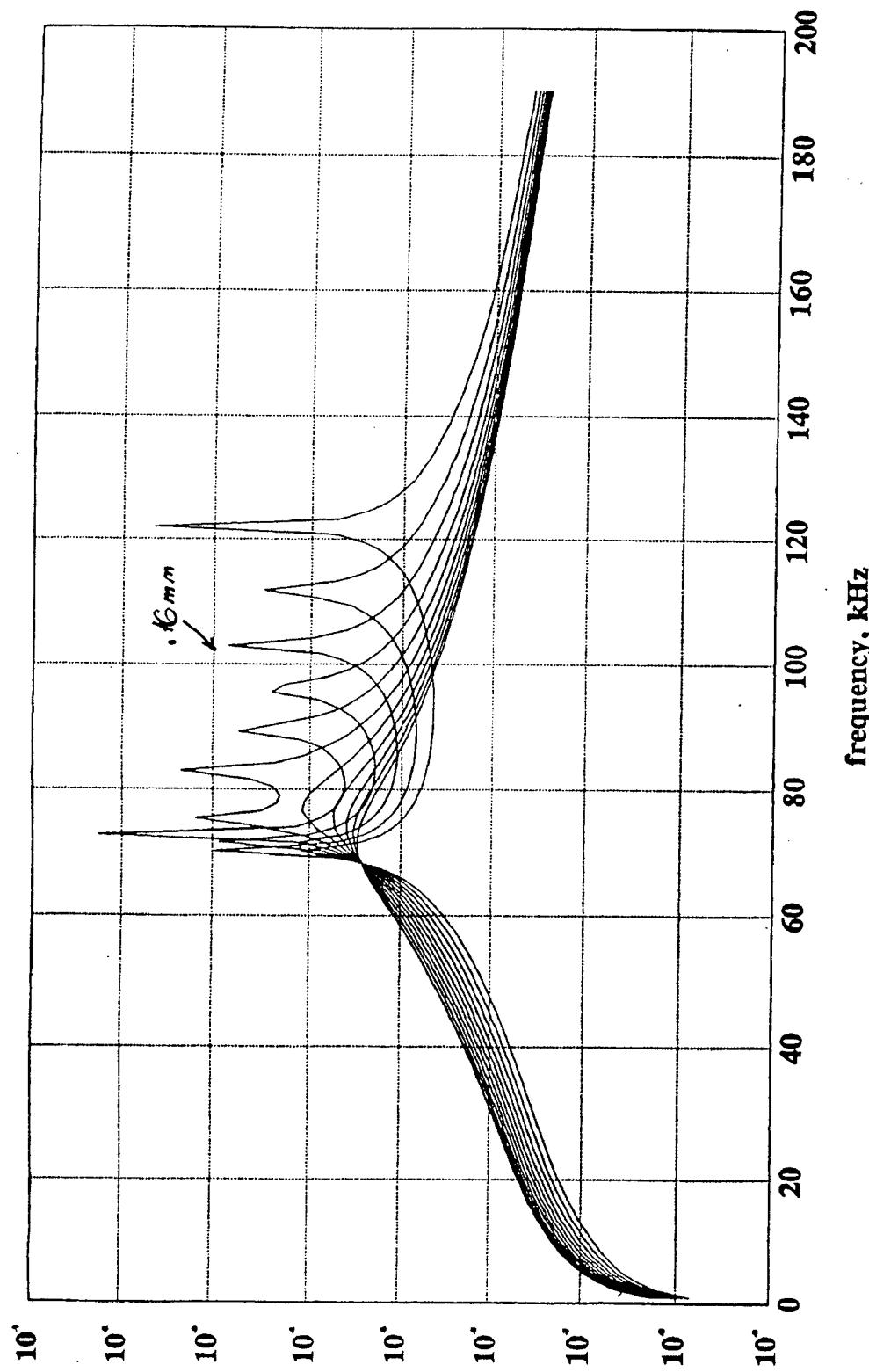


Fig. 2. Transducer velocity per volt (two layer transducer). Thickness of the backing $h_b = 0.1 \dots 0.3$ mm (varies). Thickness of the load $h_{load} = 3/8"$, grazing angle 45° , thickness of the epoxy and insulation $h_{ins} = .1$ mm (per layer), losses = 0.

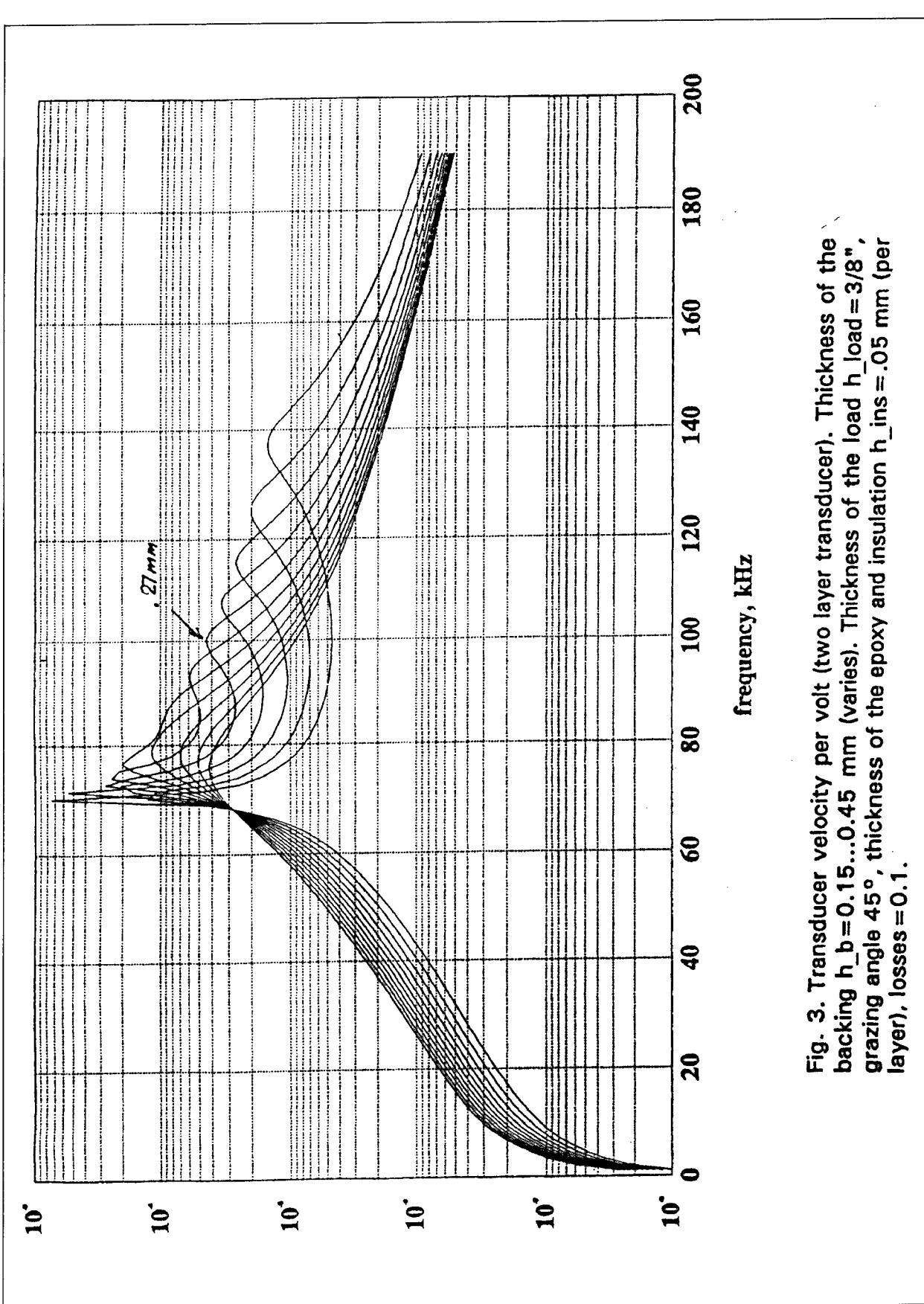


Fig. 3. Transducer velocity per volt (two layer transducer). Thickness of the backing $h_b = 0.15 \dots 0.45$ mm (varies). Thickness of the load $h_{load} = 3/8"$, grazing angle 45° , thickness of the epoxy and insulation $h_{ins} = .05$ mm (per layer), losses = 0.1.

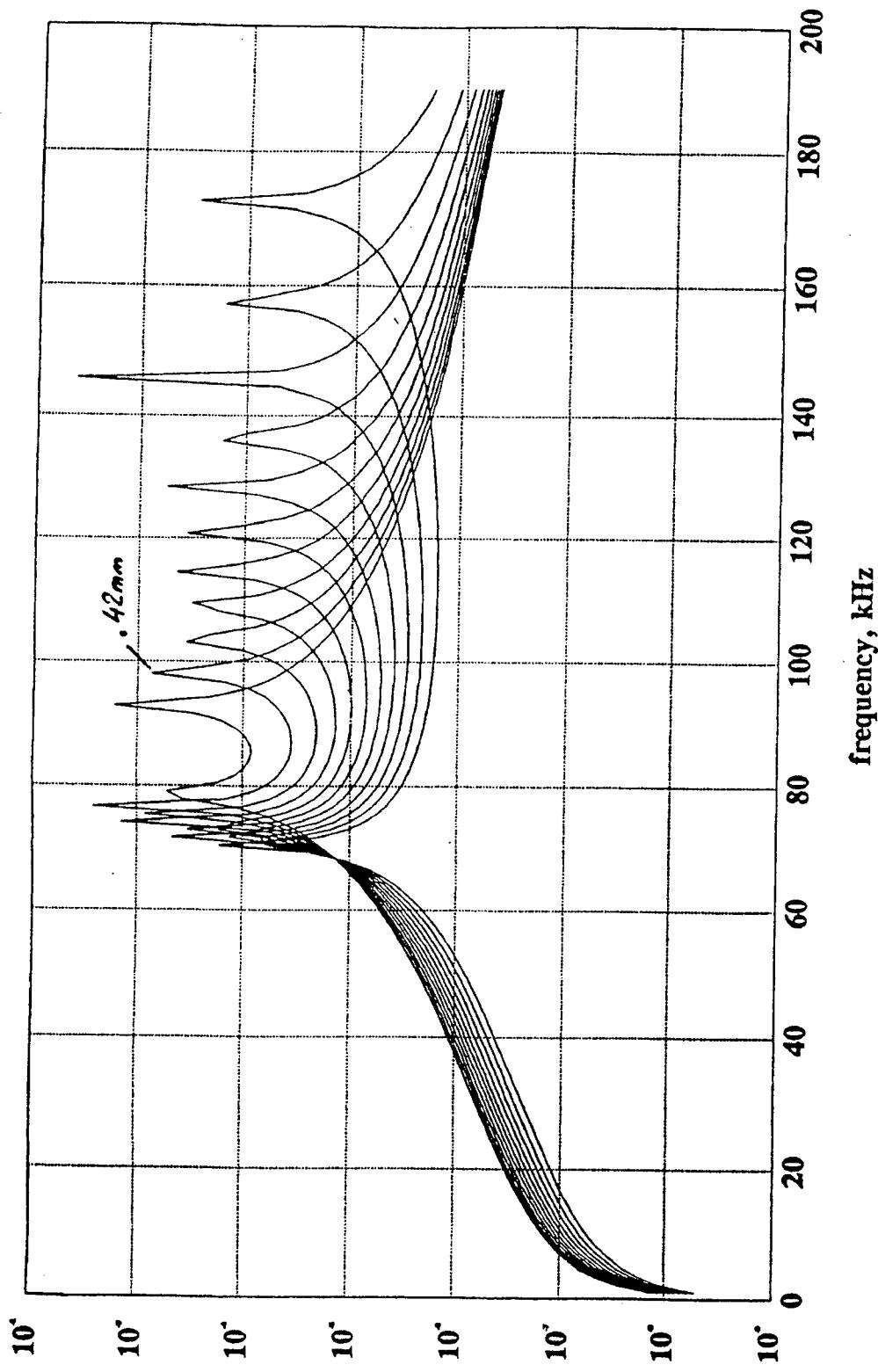


Fig. 4. Transducer velocity per volt (one layer transducer). Thickness of the backing $h_b = 0.15 \dots 0.45$ mm (varies). Thickness of the load $h_{load} = 3/8"$, grazing angle 45°, thickness of the epoxy and insulation $h_{ins} = .05$ mm (per layer), losses = 0.1.

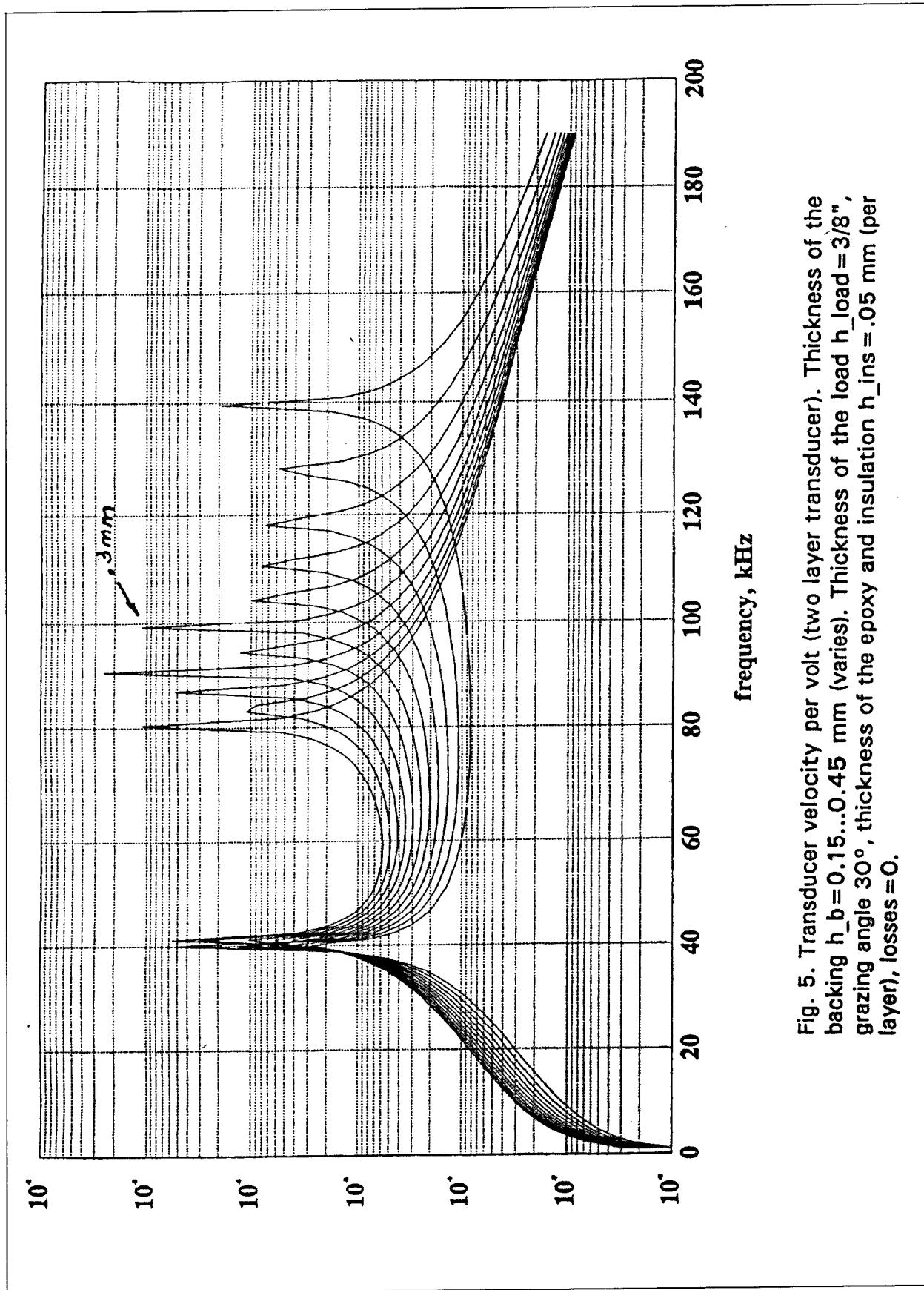


Fig. 5. Transducer velocity per volt (two layer transducer). Thickness of the backing $h_b = 0.15 \dots 0.45$ mm (varies). Thickness of the load $h_{load} = 3/8"$, grazing angle 30° , thickness of the epoxy and insulation $h_{ins} = .05$ mm (per layer), losses = 0.

Appendix E: Frequency Response of Tank and Simulation Obtained by ORE

Transducer elements (Slap-On)

FREQUENCY RESPONSE OF TANK AND SIMULATION

A simulation was run to determine the expected Waveform we would see at various frequencies from 15 to 130 KHz at 63° gazing angle. Then the 0.625 wall tank was run at those frequencies. When measuring signals on the tank arrays, the low level signals were often quite distorted and measuring their amplitude became more of an educated guess than any scientific method. (Note the graph labeled **FREQUENCY RESPONSE**)

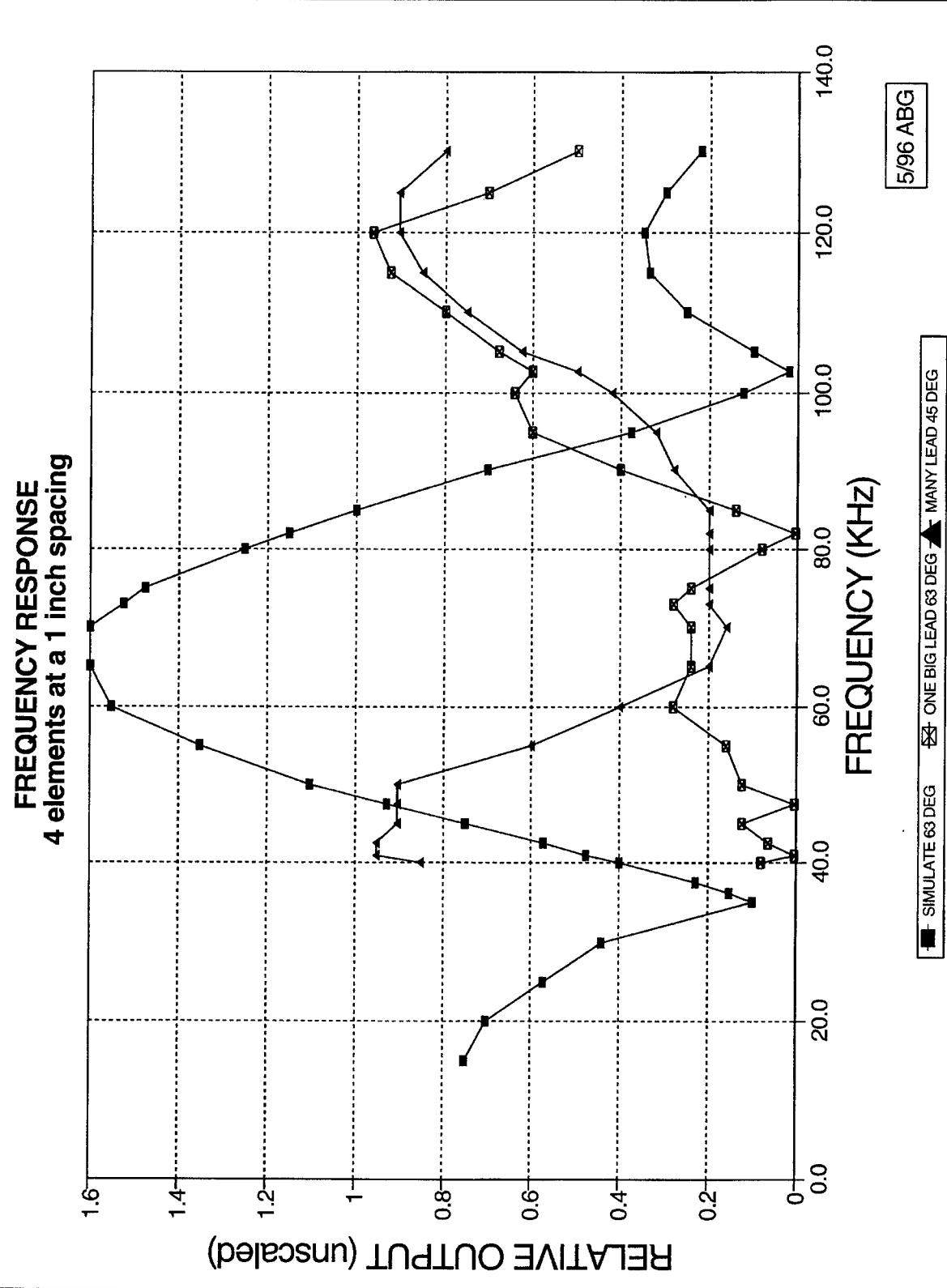
The 63° simulation shows a nice peak of reply at 60 to 70 KHZ (-3 DB from 50 to 85 KHz)

The 63° grazing angle array showed little at 60 to 70 KHz and a peak at 125 KHz There was a noticeable null at 82 KHz and also at 47.5 KHz. The 63° path has one transducer array with two thick leads and two thin leads, and the opposite transducer array with only one thick lead.

The 45° grazing angle array was compared. Both transducer arrays of the 45° array have two thick and two thin lead strips. The 45° array showed a peak at 120 KHz and also a large signal at 50 KHz. When signal levels went low, (65 - 90 KHz) no significant null was observed.

One question is:

Where did the 50 KHz reply sensitivity of the 45° degree array come from? Was it due to the elements themselves, or the physical location of the array? This prompted further tests to determine the element's frequency responses. (See TRANSDUCER IMPEDANCE AND RESONANCE below)



TRANSDUCER IMPEDANCE AND RESONANCE

After not obtaining the frequency response I expected to see, I took a look at the transducer elements. The capacitance of the elements was measured to be about .0055 μFd each (5,500 pFd). What I was looking for was the resonant frequency of the element and it's lead mass. I made a sample element using one element and a 0.90 thick lead strip on both sides. If I could measure this on the bench, I had a ghost of a chance to measure the tank mounted elements.

1. First I tried the ABG X-Y circle drawing box. It was modified to work with a lower impedance transducer, but I needed faster OP-AMPS(LM6134AIN) and the one sample I had was missing. (I ordered replacements but not due yet) The box proved useless for measurement as the elements looked like capacitors anyway.
∴ *Elements have Q and Frequency too high for XY box in its present configuration.*
2. I attempted Lissajous patterns on an oscilloscope using an R-C network (The transducer being the "C") and also a Tektronix® current probe. Both attempts proved futile.
∴ *Try something else*
3. Next I connected a square wave and a current probe to the element. That was not successful as the oscillator's output impedance damped the signal so much that it looked like an R-C spike.
∴ *Need to reduce source impedance*
4. I then tied a capacitor to the output of a power supply, and manually touching the wire, I was able to measured a well defined under damped ringing wave. Wa-La!!! we got some results. The ring was in the order of 170-180 KHz and damped down to 37% in about 9 to 10 cycles (Q is about 2 times π times number of cycles to first exponent).
∴ *The Q is about 60 to 70. Note that X_c of .0055 μFd at 180 KHz is 161 Ohms. Therefore series resistance is about 2.5 Ohms. The resistance at that level may be the lead wires and the screened Silver conductive film.*
5. I performed measurements to see what differences were. The following measurements were made with a 24 volt supply with 470 μFd /35VDC capacitor on its output and two 48" test leads clipping onto the transducer element(s)

Stand alone element (2) .090" lead (one each side) Epoxy hand set. Fr = 183 KHz
Stand alone element (2) .090" lead (one each side) Epoxy clamped. Fr = 183 KHz

∴ *Amount of epoxy is not a concern*

6. I then went to the tank with the 0.625 wall and took a look

(3)Single elements on .0625 Tank wall, one .090 lead Fr = 171, 188, 193 KHz
(4) elements arranged for 1" array, one .090 lead Fr = 179 KHz

∴ *Elements resonate singly same as when tied into an array. They don't appear to couple to each other.*

(4) elements arranged for 1" array, one .090 lead Fr = 179 KHz
 (4) elements arranged for 1" array, two .090 lead and two .035 lead Fr = 179 KHz
 ∴ *Resonance is not a function of rear mass loading. It appears the elements react in a pure momentum fashion.*

(4) elements arranged for 1" array, one .090 lead Fr = 179 KHz
 (8) elements arranged for $\frac{1}{2}$ " array, one .090 lead (double current) Fr = 180 KHz
 ∴ *Resonance appears not to be a function of array spacing or geometry. This confirms our tests earlier with single elements versus an array.*

7. I then went to the tank with the 0.375 wall and took a look.
 (1) element with one thick lead strip Fr = 157 KHz
 (4) elements as above arranged for 1" array Fr = 157 KHz
 ∴ *Resonance might be a function of tank wall. Array capacitance was measured to be also .0055 μ Fd. I am not sure of the age of the elements. It appears that they were installed using less epoxy as it is not squashed out all around the elements. They also appeared to have thinner wires attached to them.*

8. Real question is where is the ring coming from?
 Stand alone element (2) .090" lead (one each side) 48" leads Fr = 183 KHz
 Same element with leads connected directly to supply Fr = 248 KHz
 ∴ *It appears that we are doing a good job of measuring lead inductance. Where lead inductance seems to determine the major contributor of transducer tuning. It would appear that any tuning of the elements by rear mass loading or the thickness of a tank wall or array geometry is not relevant. Again this conforms to a MASS to MASS momentum type of transducer action.*

CONCLUSIONS:

Element Resonance is NOT an issue for this type of array. Any resonance is determined by wire lead inductance and not any overriding mass or tank wall loading. However, overall sensitivity may be affected by tank walls and mass loading as it appears that these elements react in a momentum type mode.

At this time it appears that the 50 KHz response that appeared on the array with a 45° grazing angle was real and that the absence of 50 KHz on the 63° array is important. Somehow 50 KHz is arriving at the correct time with the array spaced at 1".

The next question is, Where is it coming from. We suspect that signals may be arriving between the transducers by traveling down a wall of the pipe, and then across the pipe. What was observed was that the signals appeared to arrive at the same time. This next exercise is to examine alternative signal paths with the same timing or less. After considerable time, I think I have a handle on how these alternate paths time out.

Figure 1.

If we look at a point, we can zoom in on the path as it leaves a source at that point. The signal has two ways to go. Path **A** finds the signal on its way through the water with velocity V_w . Path **B** finds the signal traveling along the pipe wall, and then leaving the wall to rejoin the wave from path **A**. If the velocity ratio of the water to steel is $\cos(G)$ then the signals leave at the same time properly directing the wave front at the **Grazing angle "G"**. This is, in essence, the theory behind *Snells Law*.

If the velocity ratio of water to steel is greater than $\cos(G)$ [slower speed in Steel] then the fastest path for the signal is a direct path from the point source to its receiving transducer at the **Grazing Angle "G"**. If the velocity ratio is less than $\cos(G)$ [faster speed in Steel] then the fastest path may be up the pipe, and then down a steeper **Grazing Angle "G"** where the angle is larger and the ratio of water velocity to grazing angle velocity equal $\cos(G)$.

The graph labeled **ALTERNATE PATH TRAVEL TIME** shows the travel time of a signal from a point source set for a 45° Grazing angle. The graph shows the travel time of alternate paths through steel with a velocity of 126,000 IPS and water with a velocity of 57,600 IPS. While we might think that a travel time of about 1180 microseconds would denote a correct path and that alternate paths will be longer, such is not the case. And, in fact, at these suspected velocities, the travel times of either direct or alternate paths may appear very close to each other, it not identical. The accompanying spreadsheet shows the minimum travel time at about 62.5° grazing angle. Funny, but Snells Law calculates to 62.797°

One important concept is that the received signal can come from any number of places along the wall of the pipe simultaneously. The fact that they are all close to each other in travel time indicates that the signal may actually be an overlay of many signal bursts. The wavelength at 50,000 Hz is about 20 μSec . The delay on the spreadsheet from 1122 to 1180 μSec indicates about 3 wavelengths so we can see constructive and destructive interference.

Figure 2.

Included is a derivation showing that identical travel times can be realized if dimension "**X**" is calculated per the bottom line. Calculating "**X**" for velocities above, we see a result of 21.45 Inches from the source transducer. This places identical travel time at 2.55 inches below the center of the total path. Per the accompanying spreadsheet, we can see that this is a point almost straight across the pipe with very little diagonal component to measure flow.

ABG/tbm

Grazing angle as determined by ratio of Steel and Water sound velocities.

MULTPATH.DC2

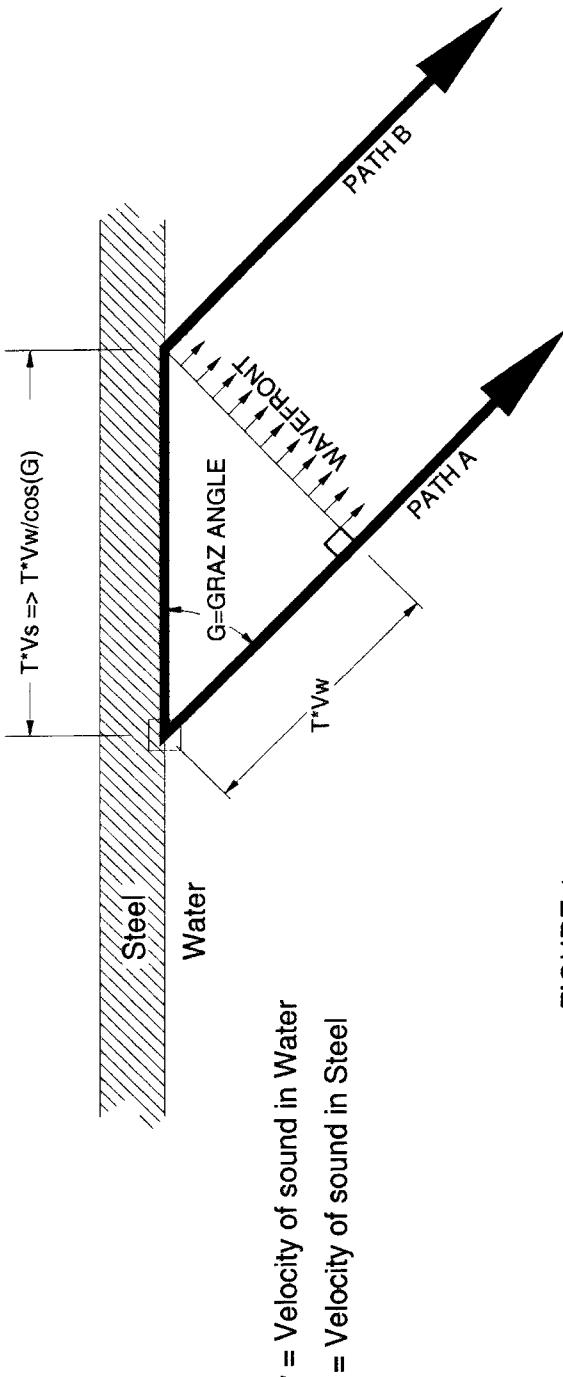
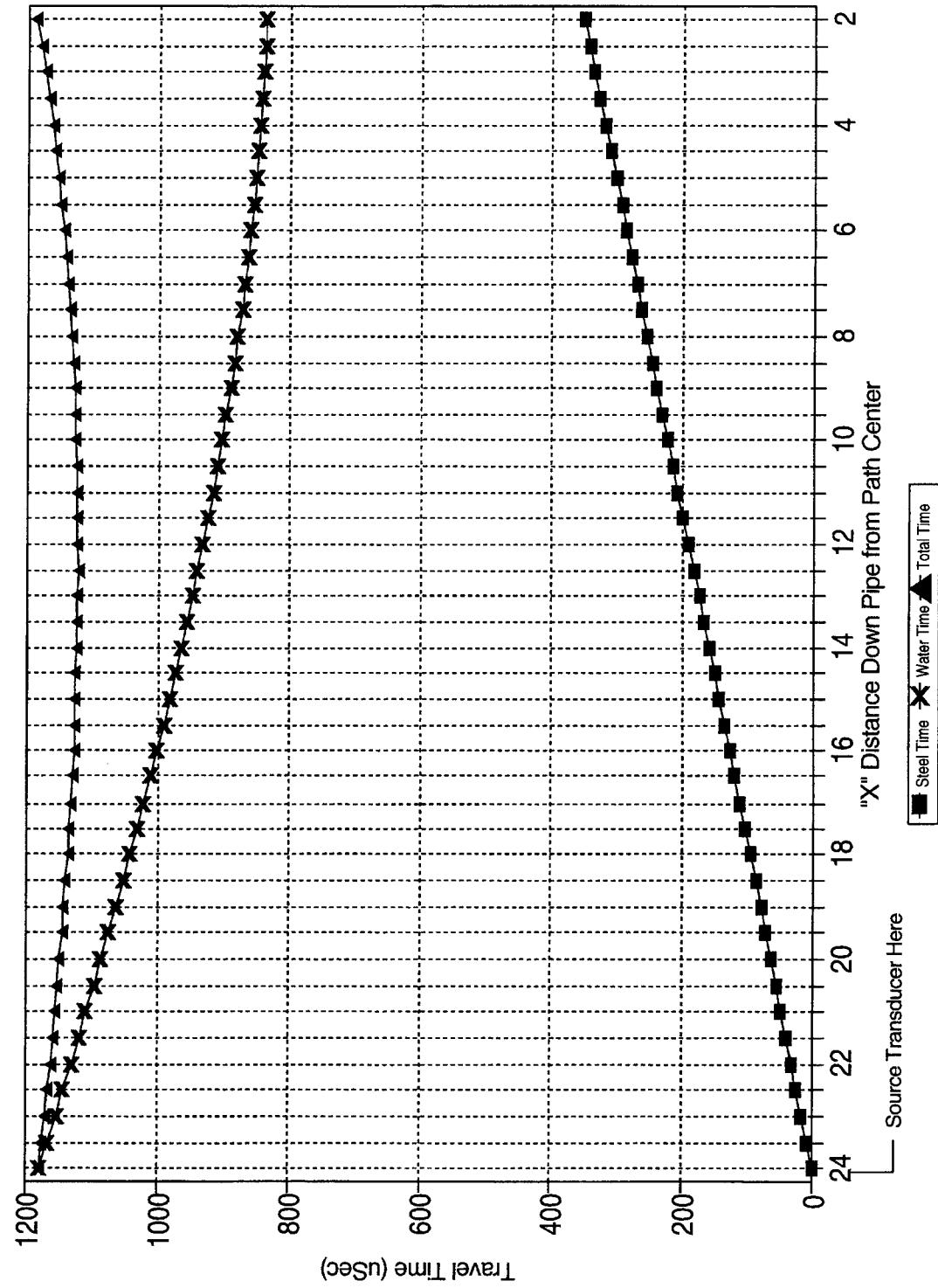


FIGURE 1

ALTERNATE PATH TRAVEL TIME

Steel Velocity = 1126,000 IPS
Water Velocity = 57,600 IPS



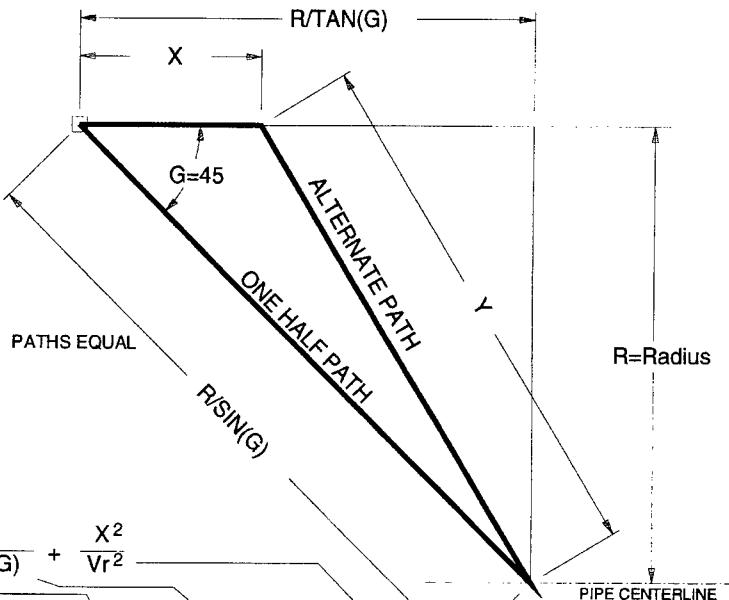
Vel of Steel (IPS) 126000
 Vel Of Water (IPS) 57600
 Pipe Radius (Inch) 24
 Xdusr Graz Angle 45

*Includes travel time for both transducers

sound leaves	Steel distance	Steel* time (uS)	Water distance	Water* time (uS)	Total time (uS)	Actual Graz Ang
Xducer	24.0	0.0	0.0	33.9	1178.5	45.0
	23.5	0.5	7.9	33.6	1166.3	45.6
	23.0	1.0	15.9	33.2	1154.2	46.2
	22.5	1.5	23.8	32.9	1142.3	46.8
	22.0	2.0	31.7	32.6	1130.5	47.5
	21.5	2.5	39.7	32.2	1118.8	48.1
	21.0	3.0	47.6	31.9	1107.3	48.8
	20.5	3.5	55.6	31.6	1096.0	49.5
	20.0	4.0	63.5	31.2	1084.8	50.2
	19.5	4.5	71.4	30.9	1073.7	50.9
	19.0	5.0	79.4	30.6	1062.9	51.6
	18.5	5.5	87.3	30.3	1052.2	52.4
	18.0	6.0	95.2	30.0	1041.7	53.1
	17.5	6.5	103.2	29.7	1031.3	53.9
	17.0	7.0	111.1	29.4	1021.2	54.7
	16.5	7.5	119.0	29.1	1011.3	55.5
	16.0	8.0	127.0	28.8	1001.5	56.3
	15.5	8.5	134.9	28.6	992.0	57.1
	15.0	9.0	142.9	28.3	982.7	58.0
	14.5	9.5	150.8	28.0	973.6	58.9
	14.0	10.0	158.7	27.8	964.8	59.7
	13.5	10.5	166.7	27.5	956.1	60.6
	13.0	11.0	174.6	27.3	947.7	61.6
	12.5	11.5	182.5	27.1	939.6	62.5
	12.0	12.0	190.5	26.8	931.7	63.4
	11.5	12.5	198.4	26.6	924.1	64.4
	11.0	13.0	206.3	26.4	916.7	65.4
	10.5	13.5	214.3	26.2	909.6	66.4
	10.0	14.0	222.2	26.0	902.8	67.4
	9.5	14.5	230.2	25.8	896.2	68.4
	9.0	15.0	238.1	25.6	890.0	69.4
	8.5	15.5	246.0	25.5	884.1	70.5
	8.0	16.0	254.0	25.3	878.4	71.6
	7.5	16.5	261.9	25.1	873.1	72.6
	7.0	17.0	269.8	25.0	868.1	73.7
	6.5	17.5	277.8	24.9	863.4	74.8
	6.0	18.0	285.7	24.7	859.0	76.0
	5.5	18.5	293.7	24.6	854.9	77.1
	5.0	19.0	301.6	24.5	851.2	78.2
	4.5	19.5	309.5	24.4	847.9	79.4
	4.0	20.0	317.5	24.3	844.8	80.5
	3.5	20.5	325.4	24.3	842.1	81.7
	3.0	21.0	333.3	24.2	839.8	82.9
	2.5	21.5	341.3	24.1	837.8	84.1
	2.0	22.0	349.2	24.1	836.2	85.2

At what point "X" does travel time
of the direct path equal the alternate path?

MULTPATH.DC2



V_w = Velocity of Water

V_s = Velocity of Steel

$V_s/V_w = V_r = \text{Velocity Ratio} \geq 1$

$$\frac{R}{V_w \sin(G)} = \frac{X}{V_s} + \frac{Y}{V_w} \quad \text{PATHS EQUAL}$$

$$\frac{R}{\sin(G)} = \frac{X}{V_r} + Y$$

$$Y = \frac{R}{\sin(G)} - \frac{X}{V_r}$$

$$Y^2 = \frac{R^2}{\sin^2(G)} - \frac{2*R*X}{V_r * \sin(G)} + \frac{X^2}{V_r^2}$$

PYTHAGOREAN

$$Y^2 = R^2 + \frac{R^2}{\tan^2(G)} - \frac{2*R*X}{\tan(G)} + X^2$$

$$R^2 + \frac{R^2}{\tan^2(G)} - \frac{2*R*X}{\tan(G)} + X^2 - \frac{R^2}{\sin^2(G)} + \frac{2*R*X}{V_r * \sin(G)} - \frac{X^2}{V_r^2} = 0$$

$$R^2 \left[1 + \frac{1}{\tan^2(G)} - \frac{1}{\sin^2(G)} \right] + \frac{2*R*X}{V_r * \sin(G)} - \frac{2*R*X}{\tan(G)} + X^2 - \frac{X^2}{V_r^2} = 0$$

THIS TERM EQUATES TO ZERO

	$1 + \frac{1}{A^2} - \frac{1}{C^2}$
$\frac{A^2 + B^2 - C^2}{A^2} = 0$	

$$\frac{2*R}{V_r * \sin(G)} - \frac{2*R}{\tan(G)} + X - \frac{X}{V_r^2} = 0 \quad \text{SO QUADRATIC TERMS DROP OUT}$$

$$X \left[1 - \frac{1}{V_r^2} \right] = 2*R \left[\frac{1}{\tan(G)} - \frac{1}{V_r * \sin(G)} \right]$$

FIGURE 2

Appendix F:

Fact Sheet



US Army Corps
of Engineers

Construction Productivity Advancement Research (CPAR)

Fact Sheet

Directorate of Research and Development
Attn: CERD-C
20 Massachusetts Avenue, N.W.
Washington D.C. 20314-1000
(P) 202-272-0257



A Corps/Industry Partnership to Advance
Construction Productivity and Reduce Costs

Fact Sheet CP-14
Date : August 1, 1996

High Accuracy Flowrate Measurement for Water Supply and Dredged Slurry Transport Pipelines.

TECHNOLOGY CHALLENGE

To develop the first externally-mountable acoustic flow meter which combines the high absolute accuracy of multi-path measurement with the economy and simplified installation of less accurate "clamp-on" flow meters for application in water supply and slurry transport industries. Such a device is not currently available in the market.

DESCRIPTION OF PROJECT

The objective of the project was to develop and manufacture a two path acoustic flow meter transceiver along with necessary signal generation and processing hardware and software. The work also included field testing of the flowmeter. A piezo-electric material known as PVDF is being used as a transducer and receiver for the acoustic instrument.

STATUS OF PROJECT

A multiple-path acoustic flowmeter was designed and fabricated. After conducting several tests in the laboratory and incorporating various modifications, an improved version of unit was manufactured. Field tests were successfully conducted on the penstock of a hydroelectric project in New York state with 30 degree and 45 degree paths using prototype equipment. Field test was also conducted on the pipeline of a dredge using a diametrical path. Both prototype and production meters successfully recorded the flow-rates while dredging. The flow meter has been patented and is now available for commercial use.

PARTNERING Corps Laboratory : Waterways Experiment Station, Vicksburg, MS
Industry Partner: ORE International Inc

COST SHARING Corps Share : \$ 500,000 Industry Partner Share : \$ 500,000

POINT OF CONTACT

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REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) The conventional techniques for high-accuracy ultrasonic flow measurement using multiple chordal paths in a pipe require drilling holes in the pipe for inserting the sensors. Under the Construction Productivity Advancement Research (CPAR) program, a research project was jointly undertaken by ORE and the U.S. Army Corps of Engineers for development of a new flow meter. The product developed is an externally mounted acoustic flow meter. The advantages of the "clamp-on" type flow meter are as follows: (a) no contact with the fluid, (b) no welding or cutting of pipe necessary, (c) no operational shutdown needed for installation, repairs, or maintenance, (d) quick and easy installation, and (e) low cost of installation. The technology consists of the following: (a) conformal phased array transducers applied to a prepared surface at four to six locations on the exterior of the pipeline, and (b) a signal processing unit that generates acoustic signals for transmission between pairs of transducers installed above; receives and time-compresses the signals; determines precise acoustic travel times between one or more transducer pairs; and employs these measured travel times to determine the flow rate using algorithms well known to the flow measurement industry. The transducers are constructed of a							
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relatively new material, PVDF. This material is found to be ideal for a flexible production transducer easily installable in the field conforming to a variety of pipe exterior dimensions.

The new meter is a differential travel-time acoustic meter. The system measures the difference in travel time between signals propagating upstream and downstream between multiple pairs of transducers. Under no-flow conditions the travel time in each direction will be the same. Under fluid flow conditions, the travel time in the downstream direction will be less than that in the upstream direction. The difference in travel time is correlated to the flow velocity. Measurement accuracy is estimated to be up to ± 1 percent of the flow.

The research project described in this report started in March 1993 and was completed in September 1996. ORE International invested an amount of \$ 500,000 for this project. In addition, the U.S. Army Corps of Engineers invested \$500,000, making this a million-dollar project. The project has produced the first acoustic flow meter that combines the high absolute accuracy of multipath measurement with the economy and simplified installation of less accurate "clamp-on" flow meters for application in water supply and slurry transport industries.